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IN THE UNITED STATES PATENT AND TRADEMARK OFFICE

Inventor(s): Thomas W. Stone and John C. Kralik

Serial No.: 10/720,816 **Examiner: Erin D. Chiem**

Filing Date: November 24, 2003 **Group Art Unit: 2883**

Title: VARIABLE OPTICAL ATTENTUATOR SYSTEMS

MAIL STOP: APPEAL BRIEF - PATENTS

COMMISSIONER FOR PATENTS
P.O. Box 1450
Alexandria VA 22313-1450

TRANSMITTAL OF APPEAL BRIEF

Sir:

Transmitted herewith is the Appeal Brief in this application with respect to the Notice of Appeal filed on August 16, 2006 .

The fee for filing this Appeal Brief is (37 CFR 1.17(c)) **$500.00**.

(complete (a) or (b) as applicable)

The proceedings herein are for a patent application and the provisions of 37 CFR 1.136(a) apply.

☐ (a) Applicant petitions for an extension of time under 37 CFR 1.136 (fees: 37 CFR 1.17(a)(1)-(5)) for the total number of months checked below:

☐	one month	$ 120.00
☐	two months	$ 450.00
☐	three months	$1020.00
☐	four months	$1590.00

☐ The extension fee has already been filled in this application.

☐ (b) Applicant believes that no extension of term is required. However, this conditional petition is being made to provide for the possibility that applicant has inadvertently overlooked the need for a petition and fee for extension of time.

Please charge to Deposit Account **50-3718** the sum of $500.00 . At any time during the pendency of this application, please charge any fees required or credit any overpayment to Deposit Account **50-3718** pursuant to 37 CFR 1.25.

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Respectfully submitted,

Thomas W. Stone and John C. Kralik

By [signature]

Jacob Erlich
Attorney/Agent for Applicant(s)

Reg. No. 24,338

Date: December 18, 2006

Telephone No. 617-345-3000

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I hereby certify that this correspondence is being deposited with the United States Postal Service as Express Mail, Label No. EV 794016522 US, in an envelope addressed to: Mail Stop Appeal Brief – Patents, Commissioner for Patents, P.O. Box 1450, Alexandria, VA 22313-1450 on December 18, 2006.

Jacob Erlich
Reg. No. 24,338

UNITED STATES PATENT AND TRADEMARK OFFICE
BEFORE THE BOARD OF APPEALS AND INTERFERENCES

Appellants:	Thomas W. Stone John C. Kralik
Serial No.:	10/720,816
Filed:	November 24, 2003
Examiner:	Erin D. Chiem
Group Art Unit:	2883
Title:	VARIABLE OPTICAL ATTENTUATOR SYSTEMS

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Denver, Colorado 80201-1920

TO: Mail Stop Appeal Brief - Patents
Commissioner for Patents
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BRIEF FOR APPELLANTS

Sir:

This is an appeal from the Final Rejection dated of June 16, 2006 of claims 1-10 in the above-identified application. This appeal is timely filed and is accompanied by the appropriate current large entity fee under 37 CFR 1.17(c).

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REAL PARTY IN INTEREST

The real party of interest is the Assignee, AVAGO TECHNOLOGIES FIBER IP (SINGAPORE) PTE. LTD. having offices at SINGAPORE, SINGAPORE .

RELATED APPEALS AND INTERFERENCES

None.

STATUS OF CLAIMS

Claims 1-10 remain pending in this application. Claim 11 has been withdrawn from consideration. No claims were allowed; claims 1-10 were rejected. The claims currently on appeal are claims 1-10. A copy of the claims on appeal is provided in the Claims Appendix.

STATUS OF AMENDMENTS

The Response After Final, dated August 16, 2006, did not amend the claims. All previously presented amendments to the claims have been entered.

The Response After Final, dated August 16, 2006, included a substitute specification as an amendment to the specification. The advisory action did not comment on whether the substitute specification was entered.

SUMMARY OF CLAIMED SUBJECT MATTER

Independent claims 1 and 8 are involved in this appeal. Dependent claims 2, 3, 4, 5, 6, 7, 9 and 10 are also involved in the appeal and are argued separately.

An optical switch/variable attenuator is claimed in independent claim 1. The optical switch/variable attenuator of claim 1 includes a polarization separating sub-system, one or more switchable transmission diffraction gratings, a polarization recombining sub-system and means for varying a diffraction efficiency of the one or more switchable transmission diffraction gratings. An embodiment is shown in Fig 1 (see also, paragraph 27, pages 7 and 8; all references herein refer to the original specification). Referring to Fig. 1, the polarization separating sub-system 30 is optically disposed to receive an input optical beam of arbitrary polarization 20 and is also being capable of separating the input optical beam into a first optical beam of a first polarization and a second optical beam of a second polarization, the second polarization being distinct from said first polarization, and emitting a first emitted optical beam of the first polarization and a second emitted optical beam of the first polarization (both beams being of the same polarization). The emitted first and emitted second optical beams constitute an input channel of the first polarization. The one or more switchable transmission diffraction gratings 40 are optically disposed to receive the input channel and capable of providing at least one transmitted channel, the at least one transmitted channel comprising at least one transmitted optical beam of the first polarization and at least one other transmitted optical beam of the first polarization. The polarization recombining sub-system 50 is optically disposed to receive the at least one transmitted optical beam of the first polarization and the at least one other transmitted optical beam of the first polarization and capable of recombining the at least one transmitted optical beam of the first polarization and the at least one other transmitted optical beam of the first polarization into at least one final output beam. One embodiment of the polarization separating/recombining sub-system includes a polarizing beam-splitter and a patterned polarization converter. Other embodiments can also be utilized in the present invention. (par. 31, p. 10)

Dependent claim 2 claims an optical switch/variable attenuator as in claim 1 in which the one or more switchable transmission diffraction gratings 40 is one switchable volume diffraction grating and which also includes a static grating. An embodiment of the optical switch/variable attenuator of claim 2 is shown in Fig. 2a. Referring to Fig. 2a, the static grating 120 is optically disposed between the switchable transmission diffraction grating 110 and the polarization recombining sub-system 50.

Dependent claim 3 claims an optical switch/variable attenuator as in claim 1 that also includes one or more control elements (45 in Fig. 1, 115 in Fig. 2a) capable of controlling switching of the one or more switchable diffraction gratings.

Dependent claim 4 claims another optical switch/variable attenuator as in claim 1 in which the one or more switchable diffraction gratings (40, Fig. 1) is one switchable volume diffraction grating and which also includes a static grating. An embodiment of the optical switch/variable attenuator of claim 4 is shown in Fig. 2b (paragraph 41, page 13). Referring to Fig. 2b, the static grating 120 is optically disposed between the polarization separating sub-system 30 and the switchable transmission diffraction grating 110.

Dependent claim 5 claims an optical switch/variable attenuator as in claim 1 in which the one or more switchable transmission diffraction gratings are two switchable volume diffraction gratings (Fig. 1, see also paragraph 27, lines 24-25, also paragraph 42, pages 13-14, referring to Figs. 2a, 2b). A first of said two switchable volume diffraction gratings is optically disposed between the polarization separating sub-system 30 and a second of the two switchable volume diffraction gratings. The second of said two switchable volume diffraction gratings is optically disposed between the first of the two switchable volume diffraction gratings and the polarization recombining sub-system 50.

Dependent claim 6 claims an optical switch/variable attenuator is in claim 2 wherein the static grating includes a transparent region. An embodiment of the optical switch/variable attenuator of claim 6 is shown in Fig. 3 (paragraph 43, p. 14).

Dependent claim 7 claims an optical switch/variable attenuator as in claim 6 that also includes two output beam ports. An embodiment of the optical switch/variable attenuator of claim 7 is shown in Fig. 3 (se paragraph 43, p. 14). The one or more output beams in claim 7 are two final output beams 260, 250. Each one of the two output beam ports 230, 240 is capable of receiving from the polarization recombining sub-system 50 one final output beam from the two final output beams 260, 250.

Independent claim 8 claims a method for providing variable attenuation of a beam (see Figs. 4a and 4b, paragraphs 51 and 52, pp. 17-18). The method includes the steps of

providing an optical system, where the optical system comprises one or more switchable volume diffraction gratings and a static grating, providing an input beam to the optical system, enabling the one or more switchable volume diffraction gratings to diffract, with a predetermined diffraction efficiency, the input beam into a diffracted beam and a transmitted beam, and, utilizing the predetermined diffraction efficiency to effect the variable attenuation of the input beam.

One embodiment of the switchable volume diffraction grating element utilized in the variable optical attenuators/1x2 switches of the claimed invention is the switchable diffraction element (grating) such as that described in U.S. Patent Ser. No. 5,771,320. Embodiments of polarization separating/recombining sub-systems utilized in the variable optical attenuators/1x2 switches of the claimed invention are described in U.S. Patent application Ser. No. 10/668,975, filed on September 23, 2003.

Dependent claim 9 claims the method of claim 8 wherein the set of switchable volume diffraction gratings comprises one switchable volume diffraction grating; and, wherein the switchable volume diffraction grating is optically disposed to receive the input beam (Fig. 4a).

Dependent claim 10 claims the method of claim 8 wherein the set of switchable volume diffraction gratings comprises one switchable volume diffraction grating; and, wherein the static grating is optically disposed to receive the input beam (Fig. 4b).

GROUNDS OF REJECTION TO BE REVIEWED ON APPEAL

The issues on appeal are:

(I) whether claims 1-5 fail to comply with the written description requirement, and

(II) whether claims 1-3 and 5-10 are anticipated by Stone (US 6,585,832 B1).

ARGUMENT

The issues on this appeal relate to the retroactive application of Federal rules and to applicability of anticipation on standards of the patent law.

Claim 1-5 were improperly rejected under 35 U.S.C. 112, first paragraph, as being based on a disclosure, which is not enabling and does not comply with the written description requirement..

In the Final Office Action, the Examiner states that "incorporating pending application 10/668975 to overcome the claim enablement rejection is not persuasive." The Examiner relies MPEP 608.01 (p), version 8, revised August 2006 which quotes 37 CFR 1.57, enacted September 21, 2004. The Applicants filed the application being considered here in on November 24, 2003. US pending application 10/668975 was incorporated by reference in the original specification. On November 24, 2003, incorporation by reference follow the rules given in MPEP 608 .01 (p), version 8, first revision, revised February 2003, and 37 CFR 1.57 had not been enacted. (A copy of the corresponding page of the Patent Rules applicable at the time the application was filed and a copy of MPEP 608 .01 (p), version 8, first revision, revised February 2003 are included in the Evidence Appendix.) Applicants respectfully state that retroactivity is not favored (see *Bowen v. Georgetown University Hospital*, 488 U.S. 204, 208 (1988)) and that the federal Administrative Procedures Act defines a rule as an agency statement of future effect (5 U.S.C.A. § 551(4)).

MPEP 608 .01 (p), version 8, first revision, revised February 2003, stated that "an application for a patent was filed may incorporate 'essential material' by reference to (1) a US patent, (2) a US patent application publication, or (3) a pending US application," where the US application does not itself incorporate "essential material" by reference. Applicants respectfully state that, according to MPEP 608 .01 (p), version 8, first revision, revised February 2003, the incorporation by reference of pending US application 10/668975 was proper for material that the Examiner deems to be "essential material," that is material necessary to describe the claimed invention or enable the claimed invention. Applicants have

further provided a substitute specification in which the relevant parts of US application 10/668975 have been copied onto the application being consider herein. (A copy of the substitute specification is provided in the Evidence Appendix.)

In the Final Office Action, the Examiner states that "incorporating US Patent 5,771,322 illustrate the disclosure of newly amended subject matter is ineffective since the patent ' 320 is a statutory 102(b) reference." US Patent 5,771,322 had been incorporated by reference in the original, as filed, specification. Applicants respectfully state that according to MPEP 608 .01 (p), version 8, first revision, revised February 2003, the incorporation by reference of essential material by reference to a US patent was proper and that most granted patents, unless the application is a continuation or a continuation by part, are candidate statutory 102(b) references. Applicants respectfully state that the incorporation by reference in the application as filed of a US patent can be used to illustrate the disclosure of an amended claim. Applicants respectfully state that the incorporation by reference in the application as filed of a US patent to incorporate by reference essential material is still permissible under 37 CFR 1.57. Applicants have copied onto the substitute specification the relevant portions of U.S. Patent 5,771,320.

Since the incorporation by reference in the original application, as filed, was proper in order to incorporate "essential material," assuming that the Examiner was correct in classifying the material in question as essential and not supported with out the incorporation by reference, the incorporation by reference by itself should be enough to properly satisfy the written description requirement. One skilled in the art would reasonably conclude that the Applicants had possession of the claimed invention. See, e.g., *Moba, B.V. v. Diamond Automation, Inc.*, 325 F.3d 1306, 1319, 66 USPQ2d 1429, 1438 (Fed. Cir. 2003); *Vas-Cath, Inc. v. Mahurkar*, 935 F.2d 1555, 1563, 19 USPQ2d 1111, 1114 (Fed. Cir. 1991). Applicants also state that the specification as originally filed supports the amended claims. (see *Enzo Biochem, Inc. v. Gen-Probe, Inc.*, 323 F.3d 956, 969-70, 63 USPQ2d 1609, 1617 (Fed. Cir. 2002).)

Therefore, Applicants respectfully state that claims 1-5 comply with the written description requirement.

Since US pending application 10/668975 provides detailed description of how to make and use the polarization separating sub-system and the polarization recombining sub-system, paragraphs 28 and 33 of the specification and U.S. Patent 5,771,320 provide details on how to make and use a switchable transmission diffraction grating, one skilled in the art could make or use the invention from the disclosures in the patent coupled with information known in the art without undue experimentation. Applicants also referred to paragraph 31 of the specification describing "a polarizing beam-splitter and a patterned polarization converter" as one embodiment of the polarization separating/recombining subsystem and to paragraphs 28-30 of the specification describing one embodiment of a switchable transmission grating. "The test of enablement is whether one reasonably skilled in the art could make or use the invention from the disclosures in the patent coupled with information known in the art without undue experimentation." *United States v. Telectronics, Inc.,* 857 F.2d 778, 785, 8 USPQ2d 1217, 1223 (Fed. Cir. 1988). Applicants respectfully state that one skilled in the art without undue experimentation, either based on paragraphs 28-31 of the specification or on US pending application 10/668975 and U.S. Patent 5,771,320, which are incorporated by reference, would be able to make and use the claimed invention.

<u>Claims 1-3 and 5-10 were improperly rejected under 35 U.S.C. §102(e) as being anticipated by Stone (US 6,585,382) - the '382 patent).</u>

There are two steps in the analysis necessary to determine whether a claim is anticipated or not anticipated by prior art.. The first step is to construe the meaning and scope of the claim at issue. *Markman v. Westview Instruments Inc.,* 52 F.3d. 968, 996, n. 7 (Fed. Cir. 1995), *affirmed* 116 S. Ct. 1384, 38 USPQ2d 1461 (1996). The second step requires a comparison of the properly construed claim with the prior art to determine whether the claims are anticipated or rendered obvious by the prior art. *Id.*

In order to anticipate a claim under 35 U.S.C. §102, it is well recognized in the law that all of the limitations found in the claims must be shown in the single reference relied upon for such a rejection. "A claim is anticipated only if each and every element as set forth in the claim is found, either expressly or inherently described, in a single prior art reference."

Verdegaal Bros., Inc. v. Union Oil Co., 814 F.2d 628 (Fed. Cir. 1987). *See Glaverbel Societe Anonyme v. Northlake Marketing & Supply Inc.*, 45 F.3d 1550, 33 USPQ2d 1446 (Fed. Cir. 1995); *Minnesota Min. & Mfg. Co. v. Johnson & Johnson Orthopedics, Inc.*, 976 F.2nd 1559, 24 USPQ2d 1321 (Fed. Cir. 1992); *Merck & Co. v. Teva Pharms. USA, Inc.*, 347 F.3d 1367, 1372 (Fed. Cir. 2003). Therefore, the comparison of the properly construed claim with the prior art must be performed by comparing each limitation, as properly construed, to the single prior act reference.

Applicants respectfully state that the '382 patent does not teach or disclose all the limitations of claim 1. The absence of all the distinct limitations of claim 1 of the Applicants' invention in the '382 patent can be understood by comparing the two inventions The '382 patent teaches volume phase holographic switchable mirrors (the '382 patent, col. 3, line 2, line 5-6). Referring to Figure 1, the '382 patent states, in col. 4, lines 35-38, that "FIG. 1 of the drawings which depicts a plurality (three being illustrated therein) of switchable mirrors (or switchable mirror arrays, used interchangeably here) 12, 14, 16." Applicants respectfully state that the '382 patent does not teach "at least one switchable transmission diffraction grating."

Applicants respectfully state that the Examiner erred in stating in the Office Action that Stone (the '3 82 patent) teaches switchable mirrors and switchable gratings interchangeably. While the Applicants were unable to find that statement in the '382 patent (the '382 patent repeatably states that "the terms switched mirrors and switchable mirrors are used interchangeably throughout the application"), even if it were so, the statement does not imply that switchable mirrors are interchangeable in the present claimed invention with switchable transmission gratings. That in fact switchable mirror can not be interchanged for the claimed switchable transmission gratings can be seen from figures 1, 2a, 2b, and 3 of the original specification. In figure 1 of the original specification, if the grating were a volume phase holographic switchable mirror a variable attenuator would not be obtained since the output would be either 1 or zero. In figures 2a, 2b, and 3 of the original specification, if the second grating is a mirror, there would be no output at the system (furthermore, replacing what is stated to be in the reference a switchable mirror with a switchable transmission grating would render the prior art non-anticipatory.) Applicants respectfully state that claim 1 is not

anticipated by the '382 patent. As described above, Applicants respectfully state that the '382 patent does not enable claims 1-7. "In order to be anticipating, a prior art reference must be enabling so that the claimed subject matter may be made or used by one skilled in the art." *Impax Laboratories v. Aventis Pharmaceuticals Inc.*, 2006 U.S. App. LEXIS 28674, (Fed. Cir. 2006) (opinion 05-1313, decided November 20, 2006). (see also *Helifix, Ltd. v. Blok-Lok, Ltd.*, 208 F.3d 1339, 1346 (Fed. Cir. 2000))

It is axiomatic that where a parent claim is not anticipated, the dependent claims cannot be anticipated. Nevertheless, for completeness and to maintain all available points, the additional limitations of claims 2-6 are compared below to the '382 patent. As will be shown below, the '382 patent does not disclose, expressly or inherently, the additional limitations of claims 2-6.

Claim 2 recites "a static grating optically disposed between said at least one switchable transmission diffraction grating and said polarization recombining sub-system." The Examiner equates the static grating to that described in col. 6, lines 6-20 of these 382 patent. Col. 5, lines 66-67 and Col. 6, lines 6-20 of these 382 patent state

> "In one of the preferred embodiments of the invention, volume phase holographic switchable mirrors are used to permit switching of the incident energy between the transmitted and reflected directions. Such switchable mirrors may be controlled by electrical switching, optical switching, and polarization switching of the mirrors, as discussed with specific embodiments of the invention. Recently it has been demonstrated that high efficiency volume diffraction gratings which are recorded in permeable media, such as the DMP-128 photopolymer manufactured by Polaroid Corporation, Cambridge, Massachusetts can be made to be rapidly switchable between high and low diffraction efficiency states under electric control by imbibing the structure with liquid crystals. In this technique, the crystals are rotated by the applied electric field and their refractive index switches in the range between ordinary and extraordinary values. By choosing the materials so that one of these switchable values of refractive index matches that of the phase modulation in the grating, the grating modulation is effectively switched "off-and-on" as the

liquid crystal "fill" material index matches and mismatches the modulation, respectively "

As can be seen from the above, the '382 patent describes volume holographic mirrors which, as Examiner states, by maintaining a constant electric field, we produce a mirror not a static grating. The '382 patent does not teach "a static grating" and neither does it teach "a static grating optically disposed between said at least one switchable transmission diffraction grating and said polarization recombining sub-system."

Applicants respectfully state that while a switchable diffraction grating may be a switchable reflective diffraction grating if it is designed to be so, that does not equates to a switchable reflective diffraction grating being interchangeable with a switchable transmission diffraction grating in the present claimed invention. Applicants respectfully state that such a difference can be seen from Samuel C. Barden, James A. Arns, and Willis S. Colbur, *Volume-phase holographic gratings and their potential for astronomical applications,* Proceedings SPIE vol. 3355, "Optical Astronomical Instrumentation" pp. 866-876, 1998, a copy of which is enclosed in the Evidence Appendix.

Regarding claims 2 and 4, the Examiner states that pixellated rotator or "pixellated retarder" is interchangeable with a "steering grating." Applicants are unable to locate a reference to that interchangeability in U.S. 5,692,077. Applicants further state that such an interchangeability does not follow the use and meaning given to those terms by those skilled in the art. A retarder is defined as "device that uses nematic liquid crystals sandwiched between fused silica substrates to change the phase of polarized light. The cell is tunable from half-wave to zero retardation because variation of the applied voltage results in different degrees of birefringence in the liquid crystal," according to the Photonics Dictionary available at
http://www.photonics.com/directory/dictionary/lookup.asp?url=lookup&entrynum=4561&letter=r A steering grating, according to the preceding definition, is not a retarder. Applicants respectfully state that such an interchangeability is not found in U.S. 5,692,077 and would be contrary to accepted optical concepts.

Claim 4 as amended recites "a static grating optically disposed between said polarization separating sub-system and said at least one switchable transmission diffraction grating." The above statements related to static gratings also applied to claim 4. Therefore, Applicants respectfully state that the '382 patent fails to teach or disclose at least one additional limitation of claim 4.

Claims 2 through 7 are dependent claim 1 and since , as stated above, claim 1 is not anticipated by the 382 patent, claims 2-7 are not anticipated by the 382 patent.

Claim 5 as amended recites "two switchable transmission diffraction gratings" The '382 patent does not teach " two switchable transmission diffraction gratings." See Figs 13a, 13b of the '382 patent as well as col. 3, line 2, line 5-6, of the '382 patent.

The method of claim 8 also uses a static grating. Since as stated above, .The '382 patent does not teach "a static grating," claim 8 is not anticipated by the 382 patent.

Claims 9-10 depend on claim 8 and since claim 8 is not anticipated by the '382 patent, claims 9-10 are not anticipated by the 382 patent.

Thus, in summary, independent Claims 1 and 8 of the Applicants' invention are not anticipated by the '382 patent and neither are any of the dependent claims.

CONCLUSION

It is quite clear from the arguments presented above that claims 1-5 comply with the written description requirement and the enablement requirement and that 1-3 and 5-10.are not anticipated by the '382 patent.

In summary, Appellants respectfully submit that claims 1-10 are clearly patentable for the aforesaid reasons and thus request this Honorable Board to reverse the decision of the Examiner.

In accordance with Section 714.01 of the M.P.E.P., the following information is presented in the event that a call may be deemed desirable by the Examiner:

JACOB ERLICH (617) 854-4000.

Dated: December 18, 2006

Respectfully submitted
on behalf of Appellants,
Thomas W. Stone et al.

By: ____________________
Jacob Erlich
Reg. No. 24,338
Attorney for Appellants

CLAIMS APPENDIX

1. (Previously presented) An optical switch/variable attenuator comprising:
a polarization separating sub-system;

at least one switchable transmission diffraction grating; and,

a polarization recombining sub-system;

means for varying a diffraction efficiency of said at least one switchable transmission diffraction grating;

said polarization separating sub-system being optically disposed to receive an input optical beam of arbitrary polarization and also being capable of separating the input optical beam into a first optical beam of a first polarization and a second optical beam of a second polarization, said second polarization being distinct from said first polarization, and emitting a first emitted optical beam of the first polarization and a second emitted optical beam of the first polarization, said emitted first and emitted second optical beams constituting an input channel of the first polarization;

said at least one switchable transmission diffraction grating being optically disposed to receive the input channel and capable of providing at least one transmitted channel, the at least one transmitted channel comprising at least one transmitted optical beam of the first polarization and at least one other transmitted optical beam of the first polarization; said at least one switchable transmission diffraction grating constituting a set of switchable transmission diffraction gratings; and,

said polarization recombining sub-system being optically disposed to receive the at least one transmitted optical beam of the first polarization and the at least one other transmitted optical beam of the first polarization and capable of recombining the at least one transmitted optical beam of the first polarization and the at least one other transmitted

optical beam of the first polarization into at least one final output beam; said at least one final output beam constituting a set of output beams.

2. (Previously presented) The optical switch/variable attenuator of claim 1 further comprising:
   a static grating optically disposed between said at least one switchable transmission diffraction grating and said polarization recombining sub-system; and,
   wherein said at least one switchable transmission diffraction grating comprises one switchable transmission volume diffraction grating.

3. (Previously presented) The optical switch/variable attenuator of claim 1 further comprising:
   at least one control element capable of controlling switching of said at least one switchable transmission diffraction grating.

4. (Previously presented) The optical switch/variable attenuator of claim 1 further comprising:
   a static grating optically disposed between said polarization separating sub-system and said at least one switchable transmission diffraction grating; and,
   wherein said at least one switchable transmission diffraction grating comprises one switchable transmission diffraction grating.

5. (Previously presented) The optical switch/variable attenuator of claim 1 wherein said set of switchable transmission diffraction gratings comprises two switchable transmission diffraction gratings;
   a first of said two switchable volume transmission diffraction gratings being optically disposed between said polarization separating sub-system and a second of said two switchable volume transmission diffraction gratings; and,
   the second of said two switchable volume transmission diffraction gratings being optically disposed between the first of said two switchable volume transmission diffraction gratings and said polarization recombining sub-system.

6. (Original) The optical switch/variable attenuator of claim 2 wherein said static grating includes a transparent region.

7. (Previously Presented) The optical switch/variable attenuator of claim 6 further comprising:

   two output beam ports; and,

   wherein said set of output beams comprises two final output beams;

   each one of said two output beam ports being capable of receiving from said polarization recombining sub-system one final output beam from said two final output beams.

8. (Previously Presented) A method for providing variable attenuation of a beam, the method comprising the steps of:

   providing an optical system, said optical system comprising at least one switchable volume diffraction grating and a static grating;

   providing an input beam to said optical system;

   enabling the at least one switchable volume diffraction grating to diffract, with a predetermined diffraction efficiency, the input beam into a diffracted beam and a transmitted beam; and,

   utilizing the predetermined diffraction efficiency to effect the variable attenuation of the input beam;

   wherein said at least one switchable volume diffraction grating constitutes a set of switchable volume diffraction gratings.

9. (Previously Presented) The method of claim 8 wherein the set of switchable volume diffraction gratings comprises one switchable volume diffraction grating; and,

   wherein the switchable volume diffraction grating is optically disposed to receive the input beam.

10. (Previously Presented) The method of claim 8 wherein the set of switchable volume diffraction gratings comprises one switchable volume diffraction grating; and,

    wherein the static grating is optically disposed to receive the input beam.

11. (Withdrawn) A method for switching one input optical beam to two output beams, the method comprising the steps of:

providing a switchable volume diffraction grating;

providing a static grating having a transparent region;

enabling said switchable volume diffraction grating to diffract, with a predetermined diffraction efficiency, the input optical beam into a diffracted beam and a transmitted beam;

diffracting, with a predetermined diffraction efficiency, the input beam into a diffracted beam and a transmitted beam;

diffracting the diffracted beam utilizing the static grating; and,

transmitting the transmitted beam through said transparent region;

wherein the diffracted beam and the transmitted beam comprise the two output beams.

THE EVIDENCE APPENDIX

SUBSTITUTE SPECIFICATION (provided in Response to Final Office Action submitted on August 16, 2006)

VARIABLE OPTICAL ATTENUATOR SYSTEMS

FIELD OF THE INVENTION

[0001] The present invention relates generally to interconnection and switching systems, and, more particularly, to optical switching/routing (interconnecting) systems which incorporate the use of selectable switching and routing components.

BACKGROUND OF THE INVENTION

[0002] In many current and future systems light beams are modulated in a digital and/or analog fashion and are used as "optical carriers" of information. There are many reasons why light beams or optical carriers may be preferred in these applications. For example, as the data rate required of such channels increases, the high optical frequencies provide a tremendous improvement in available bandwidth over conventional electrical channels such as formed by wires and coaxial cables. In addition, the energy required to drive and carry high bandwidth signals can be reduced at optical frequencies. Furthermore, optical channels, even those propagating in free space (without waveguides such as optical fibers) can be packed closely and even intersect in space with greatly reduced crosstalk between channels.

[0003] Optical attenuators perform numerous tasks associated with optical signal transmission systems. One function of an attenuator is to reduce the intensity of an optical signal which enters a photosensitive component. Photosensitive components are affected by variations in light intensity. Therefore, an

attenuator causes the light intensity to be within the dynamic range of the photosensitive components. By using an attenuator, damage to the component is precluded. Additionally, the component does not become insensitive to small changes in the optical signal.

[0004] In other applications, attenuators serve as noise discriminators by reducing the intensity of spurious signals received by the optical device to a level below the device's response threshold. Moreover, optical attenuators are used to reduce the power of optical signals from an input fiber to an output fiber, and especially to balance optical power between several lines of an optical system. Many optical attenuators are also capable of actively attenuating an optical signal. Variable attenuators are required in some applications where different optical components require dissimilar incident optical signals, and hence variable sensitivities and saturation points. A fixed (i.e., passive) attenuation device is impractical for this purpose.

[0005] Attenuators serve to maintain the light level at a constant to compensate for component aging i.e., loss of efficiency in fiber amplifiers and reduced laser output from source, and changing absorption in optical waveguides. Variable attenuators serve to control feedback in optical amplifier control loops to maintain a constant output (e.g., as an automatic gain control element (AGC)).

[0006] Some variable attenuator designs require mechanical components or a number of optical components. Both of this type of attenuators exhibit a number of characteristics that are not desirable, such as high manufacturing and assembly costs, reduced reliability and extreme sensitivity to alignment.

[0007] There is a need for low loss, reliable variable optical attenuators.

[0008] A common problem encountered in applications in which high data rate information is modulated on optical carrier beams is the switching of the optical carriers from among an array of channels. These differing optical channels may represent, for example, routes to different processors, receiver locations, or antenna element modules. One approach to accomplish this switching is to extract the information from the optical carrier, use conventional electronic switches, and then re-modulate an optical carrier in the desired channel. However, from noise, space, and cost perspectives it is sometimes more desirable to directly switch the route of the optical carrier from the input channel to the desired channel, without converting to and from the electronic (or microwave) regimes.

[0009] A problem that is typical in optical switching systems is the insertion loss they impose. Some switching systems divide the input signal power into many parts, and block (absorb) the ones that are not desired. Others use switches that are inefficient and absorb, scatter, or divert a significant part of the input signal.

[0010] A commonly utilized optical switch is a one input, two output switch, also referred to as a 1X2 switch. There is a need for low loss, reliable 1X2 switches.

[0011] It is one object of this invention to provide polarization insensitive variable optical attenuators and 1X2 switches.

[0012] It is another object of this invention to provide low loss, reliable 1X2 switches.

[0013] It is a further object of this invention to provide low loss, reliable variable optical attenuators.

BRIEF SUMMARY OF THE INVENTION

[0014] The objects set forth above as well as further and other objects and advantages of the present invention are achieved by the embodiments of the invention described hereinbelow and set out in the claims appended hereto.

[0015] Low loss, reliable variable optical attenuators and 1X2 switches and polarization insensitive low loss, reliable variable optical attenuators and 1X2 optical switches are disclosed in the present invention.

[0016] In one embodiment, a system of the present invention includes a polarization separating sub-system a polarization recombining sub-system and one or more switchable volume diffraction gratings to provide polarization insensitive low loss, reliable variable optical attenuators and 1X2 optical switches. The polarization separating sub-system is optically disposed to receive an input optical beam of arbitrary polarization and is also capable of separating the input optical beam into a first optical beam of a first polarization and a second optical beam of a second distinct, orthogonal polarization. The polarization separating sub-system is also capable of emitting a first emitted optical beam of the first polarization and a second emitted optical beam of the first polarization, the emitted first and emitted second optical beams constituting an input channel of the first polarization. The one or more switchable volume diffraction gratings are optically disposed to receive the input channel and are also capable of providing one or more transmitted channels. The one or more

transmitted channels include at least one transmitted optical beam of the first polarization and at least one other transmitted optical beam of the first polarization. The polarization recombining sub-system is optically disposed to receive the at least one transmitted optical beam of the first polarization and the at least one other transmitted optical beam of the first polarization and is capable of recombining the at least one transmitted optical beam of the first polarization and the at least one other transmitted optical beam of the first polarization into at least one final output beam of combined polarization.

[0017] For a better understanding of the present invention, together with other and further objects thereof, reference is made to the accompanying drawings and detailed description and its scope will be pointed out in the appended claims.

BRIEF DESCRIPTION OF THE SEVERAL VIEWS OF THE DRAWINGS

[0018] Figure 1 is a pictorial, schematic representation of an embodiment of the optical switching/routing system of this invention;

[0019] Figure 2 is a pictorial, schematic representation of another embodiment of an optical switching/routing system of this invention;

[0020] Figure 3 is a pictorial, schematic representation of yet another embodiment of an optical switching/routing system of this invention;

[0021] Figure 4 is a schematic representation of an embodiment of a polarization insensitive optical switching/routing system of this invention;

[0022] Figure 5 is a schematic representation of another embodiment of the polarization insensitive optical switching/routing system of this invention;

[0023] Figure 6a is a top view of a schematic representation of an embodiment of a polarization converting system of this invention;

[0024] Figure 6b is a side view of the schematic representation of an embodiment of the polarization converting system of Figure 6a;

[0025] Figure 7 is a graphical representation of a comparison of contrast for two embodiments of a polarization converter utilized in an embodiment of the polarization converting system of this invention;

[0026] Figure 8 is a flowchart of an embodiment of the method for fabricating a polarization converter of this invention;

[0027] Figure ~~1~~9 is a pictorial, schematic representation of an embodiment of a variable optical attenuator of this invention;

[0028] Figures ~~2a-2b~~10a-10b are pictorial, schematic representations of another embodiment of a variable optical attenuator of this invention;

[0029] Figure ~~3~~11 is a pictorial, schematic representation of an embodiment of a 1X2 optical switch of this invention;

[0030] Figures ~~4a-4b~~12a-12b are pictorial, schematic representations of yet another embodiment of a variable optical attenuator of this invention; and,

[0031] Figure ~~5~~13 is a pictorial, schematic representation of another embodiment of a 1X2 optical switch of this invention.

DETAILED DESCRIPTION OF THE PREFERRED EMBODIMENTS

[0032] In order to better understand the present invention described below, it should be noted that certain terms used in the description of the invention have been used interchangeably.

[0033] In the following descriptions of the present invention, the terms such as "light" and "optical radiation" may be used interchangeably, and these terms both include electromagnetic radiation over the entire spectrum of wavelengths such as, for example, ultraviolet, visible, and infrared. Also, the term "optical", for example, as applied to components and systems, refers not only to optical components and systems, but also to electro-optical components and systems.

[0034] Furthermore, terms such as "beams" and "channels" may also be interchanged, in certain instances, based upon their usage as recognized in the art.

[0035] Low loss, reliable variable optical attenuators and 1X2 switches and polarization insensitive low loss, reliable variable optical attenuators and 1X2 optical switches are disclosed hereinbelow.

[0036] Figure ~~1~~9 shows a pictorial, schematic representation of an embodiment of a variable optical attenuator (VOA) of this invention. The embodiment shown in Fig. ~~1~~9 operates in a configuration herinafter called the normally-off configuration. In one embodiment the input optical beam 420 is derived from a single-mode (SM) fiber that is coupled to a collimating lens. Other embodiments derive the input beam from collimated free space beams or collimated sources. The input optical beam 420 is a beam of arbitrary polarization. The beam 420 is received by (enters) a polarization separating sub-system 430 (also referred to as a polarization diversity filter, or a compensator), which separates the input optical beam 420 into a first optical beam

of a first polarization and a second optical beam of a second polarization, the second polarization being distinct from the first polarization (in one embodiment, the two polarizations are s- and p components). The polarization separating sub-system 430 is capable of emitting a first emitted optical beam of the first polarization and a second emitted optical beam of the first polarization (in one embodiment, the emitted beams are p-polarized). The emitted first and emitted second optical beams constitute an input channel of the first polarization. One or more switchable volume diffraction gratings 440 (one in the embodiment shown in Fig. ~~1~~9) are optically disposed to receive the input channel and are capable of providing a transmitted channel. The transmitted channel includes a first transmitted optical beam of the first polarization and a second transmitted optical beam of the first polarization. A polarization recombining sub-system 450 is optically disposed to receive the first transmitted optical beam of the first polarization and the second transmitted optical beam of the first polarization and is capable of recombining the first transmitted optical beam of the first polarization and the second transmitted optical beam of the first polarization into a final output beam 460 of combined polarization.

[0037] One embodiment of the switchable volume diffraction grating element utilized in the variable optical attenuators/1x2 switches of this invention is the switchable diffraction element (grating) such as that described in U.S. Patent Ser. No. 5,771,320, herein incorporated by reference.

[0038] The following paragraphs [0039] - [0040] are excerpted from the detailed description of U.S. Patent No. 5,771,320, herein incorporated by reference.

[0039] The embodiments of the optical switching and routing systems described herein utilize volume phase diffraction gratings that permit switching of the incident energy between two or more orders. The primary mechanisms considered which permit this diffracted-order switching are electrical switching, optical switching, and polarization switching. The switched gratings can be optically switched, electrically switched, polarization switched, or switched based on other mechanisms. Currently it is preferred that electrical and polarization switching techniques are used with the present invention since they are extremely fast (switching times in the microsecond regime or faster). Electrical switching can be obtained in materials such as Polaroid DMP-1 28 photopolymer (as described below) or, for example, polymer dispersed liquid crystals. So as to provide an example of a switching mechanism, one of the electrical switching techniques is described below. Further, switching to intermediate diffraction efficiency status permits switching of a given input signal to more than one output channel ("fan out" as opposed to "one to one" switching).

[0040] Recently it has been demonstrated in the literature that high efficiency volume diffraction gratings which are recorded in permeable media, such as the DMP-128 photopolymer manufactured by Polaroid Corporation, Cambridge, Mass., can be made to be rapidly switchable between high and low diffraction efficiency states under electric control by imbibing the structure with nematic liquid crystals. In this technique the crystals are rotated by the applied electric field and their refractive index is switched between ordinary and extraordinary values. By choosing the materials so that one of these switchable values matches that of the host grating material, the

grating modulation is effectively switched "off" and "on," thus switching the diffraction efficiency of the gratings and toggling the diffracted beam between the 0 and first diffracted order. It should also be appreciated that the switching systems described above use switched transmission diffractive gratings.

[0041] The embodiments of the optical switching and routing systems described in U.S. Patent Ser. No, 5,771,320 utilize volume phase diffraction (holographic) gratings that permit switching of the incident energy between two or more orders. The primary mechanisms considered which permit this diffracted-order switching are electrical switching, optical switching, thermal switching, and polarization switching. The switched gratings can be optically switched, electrically switched, polarization switched, or switched based on other mechanisms. Currently it is preferred that electrical and polarization switching techniques are used with the present invention since they are extremely fast (for example, switching times in the microsecond regime). Electrical switching can be obtained in materials such as liquid crystal-imbibed Polaroid DMP-128 photopolymer (as described below) or, for example, polymer dispersed liquid crystals. So as to provide an example of a switching mechanism, one of the electrical switching techniques is described below. Further, switching to intermediate diffraction efficiency status permits switching of a given input signal to more than one output channel ("fan out" as opposed to "one to one" switching).

[0042] It has been previously demonstrated in the literature that high efficiency volume diffraction gratings which are recorded in permeable media, such as the DMP-128 photopolymer manufactured by Polaroid Corporation, Cambridge, Mass., can be made to be rapidly switchable between high and low diffraction

efficiency states under electric control by imbibing the structure with nematic liquid crystals. In this technique the crystals are rotated by the applied electric field and their refractive index is switched between ordinary and extraordinary values. By choosing the materials so that one of these switchable values matches that of the host grating material, the grating modulation is effectively switched "off" and "on," thus switching the diffraction efficiency of the gratings and toggling the diffracted beam between the 0 and first diffracted order.

[0043] In some embodiments of the switchable volume diffraction grating, input beams of electromagnetic radiation with polarization in a predetermined plane of polarization are diffracted by the enabled grating. A substantially polarization insensitive variable optical attenuator (VOA)/1X2 switch can be obtained from the systems of this invention, even with polarization sensitive embodiments of the switchable gratings.

[0044] Embodiments of polarization separating/recombining sub-systems are described in U.S. Patent application Ser. No. 10/668,975, filed on September 23, 2003, incorporated by reference herein.

[0045] The following paragraphs [0046] - [0091] are excerpted from the detailed description of U.S. Patent Application Serial No. 10/668,975, incorporated by reference herein.

[0046] In order to better understand the present invention described below, it should be noted that certain terms used in the description of the invention have been used interchangeably.

[0047] In the following descriptions of the present invention, the terms such as "light" and "optical radiation" may

be used interchangeably, and these terms both include electromagnetic radiation over the entire spectrum of wavelengths such as, for example, ultraviolet, visible, and infrared. Also, the term "optical", for example, as applied to components and systems, refers not only to optical components and systems, but also to electro-optical components and systems.

[0048] Furthermore, terms such as "beams" and "channels" may also be interchanged, in certain instances, based upon their usage as recognized in the art.

[0049] The optical switching/routing systems of this invention utilize polarization converter assemblies to provide switching and routing systems with effective coupling between a first and second router assemblies, and to provide polarization insensitive switching and routing systems.

[0050] Figure 1 depicts a schematic representation of an embodiment of an optical switching/routing system 10 of this invention with effective coupling between first and second router assemblies (front half and back half) 15, 40. Referring to Fig. 1, the first router assembly 15 is capable of receiving one or more individual beams 5 of electromagnetic radiation with polarization in a predetermined plane of polarization 25. The first router assembly 15 has a predetermined orientation and includes grating means 20 defining several independently controlled segments for directing the one or more individual beams 5 of electromagnetic radiation from preselected locations 35 along the segments for input into a polarization converter assembly 30. The polarization converter assembly 30 is capable of receiving the one or more individual beams 5 of electromagnetic radiation from preselected locations 35 along the segments 20 of the first router assembly 15, and of rotating

the predetermined plane of polarization 25 to produce an output plane of polarization 45. The second router assembly 40 being has an orientation different from the predetermined orientation of the first router assembly 15. The second router assembly 40 includes grating means 20 defining several independently controlled segments for receiving each of the individual beams 5 from the polarization converter assembly 30 and directing the individual beams 5 for output 50.

[0051] Embodiments of the router assemblies are described in U. S. Patent Ser. No. 5,771,320, incorporated by reference herein. The gratings 20 are switchable gratings and the switching is controlled by control signals 12 (only two of which are shown). The gratings are separately switchable in segments 22 for each of the channels in the input array 5. This independent switching of each of the gratings 20 for each input channel can be accomplished by pixellating each of the gratings 20 into m stripe segments 22. In the embodiment shown in Fig. 1, the second router assembly 40, which is nearly identical in structure the first router assembly 15, is crossed in orientation with respect to the first router assembly 15. The segments 22 of the second router assembly 40 are rotated 90 degrees with respect to the segments 22 of the first router assembly 15.

[0052] During operation of the switching and routing system 10 of Fig. 1, control signals 12 effect the "on-off" operation of the gratings 20, thereby directing the input beams 5 of each channel to the desired output channels of output array 50. The first router assembly 15 contains n cascaded gratings 20, each of which is pixilated into m separately controllable segments 22. Thus there are n*m control signals 12 required to

independently route each of the input beams 5 to its selected column in the central plane 37. The second router assembly 40 also needs m*n control signals 12 to route the selected beam from each column to the desired output channel. The total control line count for a general m channel to m channel switch for this embodiment is thus 2*m*n.

[0053] The embodiments of the optical switching and routing systems described in U. S. Patent Ser. No. 5,771,320 utilize volume phase diffraction gratings that permit switching of the incident energy between two or more orders. The primary mechanisms considered which permit this diffracted-order switching are electrical switching, optical switching, and polarization switching. The switched gratings can be optically switched, electrically switched, polarization switched, or switched based on other mechanisms. Currently it is preferred that electrical and polarization switching techniques are used with the present invention since they are extremely fast (switching times in the microsecond regime or faster). Electrical switching can be obtained in materials such as Polaroid DMP-1 28 photopolymer imbibed with nematic liquid crystals or, for example, polymer dispersed liquid crystals. The gratings formed utilizing polymer dispersed liquid crystals or photopolymer imbibed with nematic liquid crystals are polarization sensitive gratings.

[0054] Referring again to Fig. 1, during operation of the optical switching and routing system 10 of this invention utilizing polarization sensitive gratings, control signals 19 effect the "on-off" operation of the gratings 20. Input beams 5 of electromagnetic radiation with polarization in a predetermined plane of polarization 25 are steered by the

enabled segments 22 of gratings 20 to preselected locations on the output plane 37 of the first router assembly 15. When a particular grating segment 22 is "on," the beam incident on that segment is completely switched by diffraction with little or no loss from the incident beam to a diffracted beam traveling in a new direction. The steered beams 5 from the preselected locations on the output plane 37 of the first router assembly 15 are inputs to the polarization converter assembly 30. The polarization converter assembly 30 rotates the predetermined plane of polarization 25 into an output plane of polarization 45. The output plane of polarization 45 is chosen so that the beams 5 are effectively transmitted by the second router assembly 40. The beams 5 of electromagnetic radiation with polarization in an output plane of polarization 45 are steered by the enabled segments 22 of gratings 20 in the second router assembly 40 to an output location in output array 50.

[0055] Figure 2 is a schematic representation of an embodiment of the optical switching/routing system of Fig. 1 in which the polarization converter 30 includes a liquid crystal spatial light modulator (SLM). In this embodiment, the SLM has two states. In one state, an SLM pixel rotates the polarization plane by 90°; in the other state, the polarization plane is not rotated. Exemplary embodiments are 2-D SLMs based on ferroelectric liquid crystals (such as those available from Displaytech), or SLMs based on nematic liquid crystals (such as those available from Meadowlark Optics). Other embodiments include an SLM based on a twisted nematic configuration. The SLM polarization converter 60 also includes steering gratings directly before and directly after the central plane SLM. In one embodiment, a first steering grating, disposed between the

output plane 37 and the SLM, would steer beams 5 normal to the output plane 37 of the first router assembly 15. The second steering grating, disposed after the SLM, would steer the beams 5 in the input vertical plane of the second router assembly 40. The first steering grating ensures normal (perpendicular) incidence of the beams 5 onto the SLM. The steering gratings may be pixilated static gratings or switchable gratings.

[0056] Figure 3 is a schematic representation of an embodiment of the optical switching/routing system of Fig. 1 in which the polarization converter 30 includes a half-wave retarder. In this embodiment, the polarization converter 70 includes a zero-order half-wave retarder that has its optic axis in a plane parallel to the output plane 37 of the first router assembly 15. The optic axis is oriented at 45° with respect to the polarization plane 25 of the incident beams. The polarization converter 70 also includes steering gratings directly before and directly after the central plane half-wave retarder. In one embodiment, a first steering grating, disposed between the output plane 37 and the half-wave retarder, would steer beams 5 normal to the output plane 37 of the first router assembly 15. The second steering grating, disposed after the half-wave retarder, would steer the beams 5 in the input vertical plane of the second router assembly 40. The first steering grating ensures normal (perpendicular) incidence of the beams 5 onto the half-wave retarder.

[0057] In one embodiment, half-wave retarders are comprised of anisotropic materials. In another embodiment, the half-wave retarder utilizes a solid twisted nematic film in the central plane. Such a solid twisted nematic film could include, but are not limited to, polymerizable nematic, or chiral nematic, liquid

crystals. (Examples of half-wave retarders can be found in the products offered by Meadowlark Optics and Newport Research Corporation.) Other embodiments of half-wave retarders are within the scope of this invention.

[0058] A schematic representation of an embodiment of a polarization insensitive optical switching/routing system 100 of this invention is shown in Figure 4. Referring to Figures 4and 5, the polarization components are, as is usually done, defined with respect to the local interface. In an embodiment of the grating based switching/routing system shown in Figs. 1, 2, and 3, if a pair of beams with "p" polarization constitute the input channel to the grating based switching/routing system, where the gratings diffract "p" polarized light when the gratings are "on", the polarization of the output channel of the first router assembly 15 is rotated ninety (90) degrees by the polarization converter assembly 30 and provided as input to the second router assembly 40. In this embodiment, the gratings (segments) of the second router assembly 40 are rotated 90 degrees with respect to the segments of the first router assembly 15. Since the gratings in the second router assembly 40 diffract "p" polarized light when the gratings are "on" and the polarization components are defined locally with respect to the grating, the polarization component of the output channels of the second router assembly 40 will be labeled as a "p" component although the polarization component of the output channels is rotated by 90 degrees with respect to the polarization component of the input channels to the first router assembly 15.

[0059] Referring to Fig. 4, the polarization insensitive optical switching/routing system 100 includes a polarization separating sub-system 110, a selectable switching/routing sub-

system 120, and a polarization recombining sub-system 130. The polarization separating sub-system 110 includes a polarization splitter 140 and a patterned polarization converter 150. ("Patterned" as used herein includes a "tiled" polarization converter. A "tiled" polarization converter is one that has assembled from sub-units or components.) The patterned polarization converter 150 has an isotropic region 152 and a second region 155 such that an optical beam 105 with arbitrary polarization state incident on the polarization splitter 140 will exit the patterned polarization converter 150 as two beams with parallel polarization vectors 125.

[0060] The polarization recombining sub-system 130 includes a patterned polarization converter 160 and a polarization combiner 170. The patterned polarization converter 160 has an isotropic region 162 and a second region 165 such that two beams with parallel polarization vectors 135 incident on the patterned polarization converter 160 will exit the polarization combiner 170 as an optical beam 175 with arbitrary polarization state.

[0061] If selectable switching/routing sub-system 120 includes polarization sensitive gratings, the gratings operate on one component of polarization (labeled "p" in Fig. 4). In order to make the switching/routing system 120 function with the other component of polarization (labeled "s" in Fig. 4) or with light containing both components of polarization, the switching systems are placed between symmetric polarization splitter 110 and combiner 130 assemblies as shown in Fig. 4. Although "p" and "s" are used herein as polarization labels, it should be noted that "p" and "s", and "ordinary" and "extraordinary", as used herein refer to exemplary polarization labels and the methods of this invention are not limited to these exemplary cases. It

should also be noted that the methods of this invention can be applied to, but are not limited to, orthogonal polarization components.

[0062] During operation of the system of Fig. 4, an optical beam 105 with arbitrary polarization state is incident on the polarization splitter 140. In one embodiment, the polarization splitter 140 includes a uniaxial crystal such as calcite, quartz, etc. The thickness of the splitter 140 is selected so that the s and p components are spatially separated into a pair of twin beams. The twin beams then encounter the patterned polarization converter 150 that rotates the s component beam into the p -polarized state. In one embodiment, the pattern is selected so as to leave the p-polarized beam in the p state. The two p-polarized twin beams 125 corresponding to each input beam 105 then propagate through the switching/routing system 120, and are routed accordingly. In one embodiment, the patterned polarization converter 150, 160 includes a polymerized twisted nematic rotator.

[0063] At the output of the switching/routing system 120, the exiting twin beams 135 are then symmetrically recombined. In order to balance path lengths of the two component beams, the patterned polarization converter 160 is now aligned so that the beam that was transmitted through the splitter (undeviated) at the front of the system is now deviated symmetrically as shown in Fig. 4. The thickness of the combiner 170 is chosen so that the two polarization component beams 162, 165 are brought back together again and are spatially combined in an output optical beam 175 with arbitrary polarization state.

[0064] In another embodiment of the a polarization insensitive optical switching/routing system 100, shown in Fig.

5, polarization sensitive gratings 175, 180, 185, 190 are used to accomplish the split and combine functions. The polarization sensitive gratings 175, 180 are used to split and separate the s and p polarization components into twin, spatially separated beams 152, 155 as in Fig. 4. And as in Fig. 4, a patterned polarization converter 150 produces two p-polarized twin beams 125 corresponding to each input beam 105. The two p-polarized twin beams 125 corresponding to each input beam 105 then propagate through the switching/routing system 120, and are routed accordingly. At the output of the switching/routing system 120, the exiting twin beams 135 are then symmetrically recombined. The patterned polarization converter 160 operates as in Fig. 4. The polarization sensitive gratings 185, 190 spatially combine the two polarization component beams 162, 165 into the output optical beam 175 with combined (arbitrary) polarization state. Also as in Fig. 4, the recombination is symmetric so as to balance the path lengths of the two twin polarization component beams.

[0065] In one embodiment of the polarization insensitive optical switching/routing system 100, the optical switching/routing system of Fig. 1 is utilized as the selectable switching/routing sub-system 120. In the embodiment of this invention in which the switching/routing system 120 includes a pixilated switchable grating, such as that shown in Figure 1, the two p-polarized twin beams 125 are typically switched/routed together (in tandem) in the same manner a single beam (channel) is switched through the switching/routing system 120.

[0066] It should be noted that the polarization separating/ recombining sub-systems could be considered as a separate optical systems (also referred to as a polarization diversity

filters). The polarization sensitive grating based polarization diversity filters (PDF) have cost advantages (in particular at large aperture). Multi channel capabilities (for example, a single large aperture grating can accept many parallel input channels) absent in prior art splitters, such as anisotropic and micro-optic polarization beam splitters, can be achieved in polarization sensitive grating based PDFs. Since only two components are required and these two components are readily alignable, the polarization sensitive grating based PDFs have alignment advantages over multi-element PDFs such as micro-optic polarization beam splitters.

[0067] In one embodiment, shown in figure 5, a pair of identical polarization sensitive volume holographic diffraction gratings 175,180, such as described in U.S. Patents 5,771,320, and 5,692,077, or made with PDLC, with a photo-polymer such as Polaroid DMP-128, or with dichromated gelatin, which diffract only "p" polarized light and transmits "s" polarized light are used as polarization splitting gratings. The first grating diffracts the "p" polarized light while the "s" polarized light is transmitted undiffracted.

[0068] The second grating subsequently diffracts the "p" component in order to render it parallel to the undiffracted "s" polarization component. The separation between the two gratings is sufficient to spatially separate the "s" and "p" component beams. It should be noted that the diffraction angle (and accordingly the spatial frequency) of the two grating can be chosen to optimize the contrast in the polarization splitting.

[0069] For the polarization sensitive grating shown in figure 5, the diffraction efficiency of the "p" polarization is maximized and the diffraction efficiency for "s" polarization is

simultaneously minimized (thus, the "s" polarized beam is transmitted). It should be noted that in another embodiment (not shown), the "s" polarization is maximized and the diffraction efficiency for "p" polarization is simultaneously minimized. The polarization combining performed by the polarization combining gratings 185, 190 is symmetrical to the operation of the polarization splitting gratings 175, 180. The embodiment shown in Figure 5 results in an optical path balanced system and substantially reduces the temporal chromatic dispersion effects.

[0070] A schematic representation of an embodiment of a polarization converting system 200 (patterned polarization converter) of this invention, which can be utilized as the patterned polarization converter 150, 160 of Figs. 4, 5, is shown in Figs. 6a, 6b. A detailed description of the polarization converting system 200 and methods for fabricating one embodiment are given herein below.

[0071] Referring to Figs. 6a and 6b, the polarization converting system 200 of this invention includes a polarizing beam-splitter 220 and a patterned polarization converter 230, both of which are more fully described below. During use, as seen in Figs. 6a and 6b, a substantially collimated optical beam 215 with arbitrary polarization state is incident on the system 200 through the beam-splitter light receiving surface 240 and exits as two beams 225, 235 with parallel polarization vectors, as shown in Figs. 6a and 6b. The beam-splitter light emitting surface 255 has two areas - a first area 260 and a second area 265. The polarization beam-splitter separates the received beam of light 215 into a beam of light 245 of a first polarization (also called the ordinary polarization) emitted from the first area 260 and another beam of light 250 of a second polarization

(also called the extraordinary polarization) emitted from the second area 265.

[0072] In one embodiment, the polarization converter 230 of this invention has a first isotropic region 270 and a second region 275. When a substantially collimated optical beam 215 with arbitrary polarization state is used as input to the polarizing beam-splitter 220, the beam of light of the first (the ordinary polarization) polarization 245 enters the isotropic region 270, at normal incidence, through the first region light receiving surface 280 and exits, as a beam 225 of the same first polarization, through the first region light emitting surface 285. Thus, transport through the isotropic region leaves the polarization unchanged. The output beam 225 has the same polarization as input beam 245.

[0073] The beam of light of the second (the extraordinary polarization) polarization 50 enters the second region 275, at normal incidence, through the second region light receiving surface 290 and exits, as a beam 235 of the first polarization, through the second region light emitting surface 295. Transport through the second region rotates the polarization of the incoming beam 250 producing an output beam 235 of the same polarization as the beam 225 emitted from the isotropic region. Both beams 225 and 235 exit the polarization converter 230 normal to the surface.

[0074] The first region light receiving surface 280 is substantially disposed on the first area 260 of the beam-splitter light emitting surface 255 by being in contact with or secured on area 260 by means of any conventional optically appropriate adhesive. The second region light receiving surface 290 is substantially disposed on the second area 265 of the

beam-splitter light emitting surface 255 by also being in contact with or secured on area 265 by means of any conventional optically appropriate adhesive.

[0075] While the above embodiment is described in terms of a substantially collimated optical beam with arbitrary polarization state, containing both ordinary and extraordinary polarization components, incident on the beam-splitter light receiving surface, the embodiment could be also utilized for the case where the incident substantially collimated optical beam contains only ordinary or extraordinary polarization. In this case, one of the two beams entering the polarization converter has null amplitude and the same beam also has null amplitude upon exiting the polarization converter.

[0076] Although not limited thereto, anisotropic crystalline materials, such the "walk-off polarizer" offered by Optics for Research, Inc. of Caldwell, NJ, can be utilized for the polarizing beam-splitter. It should be noted that other configurations are possible utilizing one or more sub-elements. For example, micro-optic polarizing beam splitters (including polarizing cube beam splitters) can also be utilized.

[0077] In another embodiment of the polarization converting system of this invention, a pair of polarization sensitive gratings is used as the beam splitter.

[0078] Possible, but not limited to, embodiments of the second region 275 of polarization converter 230 are a half-wave retarder and a twisted nematic polarization converter. As shown in Figs. 6a and 6b, the polarization converter 230 is utilized at normal incidence.

[0079] For a better understanding of the present invention, reference is now made of the following analysis. More

specifically, bandwidth considerations can be used to compare the half-wave retarder and a twisted nematic embodiment. For linearly polarized light incident on a half-wave retarder with its plane of polarization at 45° with respect to the optic axis (of the retarder), the optical power P_m still remaining polarized parallel with the incident light is given by

$$P_m = \cos^2\left(\frac{m\pi}{2}\frac{\lambda_c}{\lambda}\right), \qquad (1)$$

where, λ_c is the center wavelength of the incident light, λ is the wavelength of incident light and m is the order of the retarder, with m=1,3,5… for zero-, first, second-order waveplates *etc*. Note that $\lambda_c = 2\Delta nd$, where Δn is the retarder birefringence and d is the retarder thickness. It is apparent from Eq. (1) that the zero-order half-wave retarder (i.e. m=1) has the broadest bandwidth. In addition, it is the least sensitive to angle of incidence variations. The extinction ratio, or contrast, of the retarder may be defined as follows:

$$\gamma_m = 10\log P_m . \qquad (2)$$

[0080] Next, consider the 90° twisted nematic (TN) polarization converter. The optical power at the output of a 90° TN with polarization plane parallel to that of the incident light is given by

$$P_q = \frac{\sin^2\left[\frac{\pi}{2}\sqrt{1+\left(\frac{\lambda_c}{\lambda}\sqrt{4q^2-1}\right)^2}\right]}{1+\left(\frac{\lambda_c}{\lambda}\sqrt{4q^2-1}\right)^2}, \qquad (3)$$

where λ is the design wavelength and q is referred to as the order of the TN; q=1,2,3… refer to first-, second-, third-minimum TNs *etc* (as shown by C.H. Gooch and H.A. Tarry, J. Appl. Phys. D 8, 1575 (1975)). The center wavelength of the TN rotator is given by $\lambda_c = 2(\Delta n d)/(4q^2-1)$, where Δn is the nematic birefringence and d is the TN film thickness. In the case of the TN, the first-minimum TN has the broadest spectral bandwidth. The extinction ratio, or contrast, of the TN is written analogously with Eq. (2).

[0081] Figure 7 is a graphical representation of the contrast of the zero-order retarder and the first-minimum TN as a function of wavelength for λ_c=1550 nm. As can be seen from Fig. 7, the bandwidth of the first-minimum TN is broader than that of the zero-order retarder.

[0082] UV-curable nematic (N) or chiral nematic (N*), such as the RM (reactive mesogens) line of UV-curable nematics from EM Industries of Hawthorne, NY, could be used to construct the patterned polarization converter 230. The N material could be used to construct retarder-based rotators, and the N or N* material could be used to make the TN rotators.

[0083] Figure 8 depicts a flowchart of an embodiment of the method for fabricating an embodiment of the polarization converter 230. Referring to Fig. 8, first, a cell (also referred to as a receptacle) is constructed to contain and align the UV-

curable nematic (step 310, Fig. 8). The cell will generally consist of two substrates separated by appropriately sized spacers. The inner substrate surfaces will be coated with an alignment layer that aligns the nematic along a desired direction. In the case of the retarder, the alignment direction of the top and bottom substrates is the same; for the TN, the alignment directions of the top and bottom substrates are perpendicular. A suitable alignment layer that could be used is a polyimide film provided by Brewer Science (Rolla, MO) that contains mechanically-sculpted furrows to align the nematic directors. For example, polyimide SE812 (sold by Brewer Science) is spin-coated onto clean glass substrates to about 1-μm thickness, baked, then mechanically rubbed with a soft cloth. Nematic molecules align on such a polyimide layer, parallel to the rubbing direction.

[0084] Next, the cell is filled with the UV-curable nematic (step 320, Fig. 8). Filling may take place via capillary action; heating the cell may be necessary if the nematic materials are viscous. Alternatively, the nematic material may be heated on a single substrate that has spacers dispersed on it. A second substrate may be placed on top of this to create a nematic sandwich when the nematic is in the liquid state. Alternatively, the nematic may be solvent-cast onto a single substrate, as described, for example, in U.S. Patent No. 5,926,241, issued to William J. Gunning, III on July 20, 1999 (see, specifically, col. 6, lines 6-13).

[0085] The nematic-filled cell is annealed (step 330, Fig. 8) until the liquid crystal achieves the desired configuration dictated by the alignment layers on the substrates: e.g. planar or TN.

[0086] A mask is placed in contact with the filled, annealed cell so that the open areas define where the polarization rotation regions of the film shall be (step 340, Fig. 8). The film temperature is adjusted to achieve the desired layer anisotropy (step 345, Fig. 8), as determined using an optical measurement. In this step, the nematic birefringence Δn is thermally tuned after it is introduced into a cell with fixed thickness d. Note that the polarization state of an optical beam exiting the polarization converter depends on the quantity $\Delta n \cdot d / \lambda$ for both the half-wave retarder and twisted nematic configurations where λ is the wavelength of the optical beam.

[0087] The mask is, then, exposed with UV light that is effective for curing the nematic (step 350, Fig. 8). After the nematic is cured, the mask is removed (step 360, Fig. 8) and the cell is heated above the clearing temperature of the un-cured nematic (step 370, Fig.8). The unexposed areas will then become isotropic; when this state has been achieved, the entire cell is flooded with UV light to cure the isotropic regions (step 380, Fig. 8). After exposure, the nematic film is allowed to return to room temperature (step 390, Fig.8).

[0088] It should be noted that the although the above described embodiments have been described in terms of polarization rotation, other polarization conversion mechanisms are also within the scope of this invention. It should also be noted that although the embodiments of the polarization converter of this invention described above include a first isotropic region and a second polarization converting region, polarization converters including two polarization converting regions are also within the scope of this invention.

[0089] It should be further noticed that although the embodiment of the polarization insensitive switching/routing system of this invention described above includes a patterned polarization converter having an isotropic region and a polarization converting region, polarization insensitive switching/routing system including other polarization converters having two polarization converting regions are also within the scope of this invention.

[0090] An embodiment of a polarization insensitive switching/routing system of this invention including a polarization separating sub-system being capable of separating an input optical beam into a first optical beam of a first polarization and a second optical beam of a second polarization and emitting a first emitted optical beam of a third polarization and a second emitted optical beam of the third polarization, wherein the selectable switching/routing sub-system is capable of switching/routing the first emitted optical beam and the second emitted optical beam to an output channel of a fourth polarization, the output channel constituting a pair of output beams of said fourth polarization, and wherein the polarization recombining sub-system is capable of recombining the pair of output beams of the fourth polarization into a final output beam of combined polarization, is also within the scope of this invention. In such an embodiment, the polarization converters in either the polarization separating sub-system or the polarization recombining sub-system (or both) could include two polarization converting regions.

[0091] It should be noted that, although the invention is described above in terms of an embodiment where the two beams with parallel polarization vectors exiting the polarization

converter have ordinary polarization, other embodiments are possible. For example, an embodiment in which the two beams with parallel polarization vectors exiting the polarization converter have extraordinary polarization is also possible.

[0092] As described in U.S. Patent application Ser. No. 10/668,975, one embodiment of the polarization separating/recombining sub-system includes a polarizing beam-splitter and a patterned polarization converter. Other embodiments can also be utilized in the present invention.

[0093] During operation of the normally-off configuration of the embodiment shown in Fig. ~~1~~9, in the off-state (i.e. where the grating 440 is diffracting or "on") the grating 440 diffracts light into the first-order with high diffraction efficiency, and very little light propagates to the VOA output 460. In the on-state (i.e. where the grating 440 is non-diffracting or "off), the optical beam propagates through the grating 440 with very little loss and eventually, exits the VOA to the output 460. Since the diffraction efficiency of a switchable transmission volume grating varies continuously with applied voltage, the output optical power of the VOA of this invention is therefore continuously variable.

[0094] A common mode for switchable gratings fabricated using PDLC materials is to be diffracting when un-powered and non-diffracting when powered. For VOAs, it is often important to know the state of the devices in case of a power failure. If a VOA of Figure ~~1~~9 was made using such a grating, a lack of electrical power would leave the grating in a diffracting state, with little or no optical power transmitted to the output, and thus this configuration has been termed a "normally-off" configuration. It should also be noted that it is also possible

to fabricate switched gratings, including PDLC switched gratings, so that they are non-diffracting without applied electrical power, and diffracting when powered. When this alternative type of switched grating is used with the configurations of this invention, the sense of "normally-off" and "normally-on", as used herein, are reversed.

[0095] It should be noted the voltage is only one embodiment of the means for controlling the switching of the switchable grating 440. Other embodiments exist for optical switching and for polarization switching.

[0096] It should also be noted that for the VOA configuration of Figure ~~1~~9, additional switched gratings 440 may be cascaded and simultaneously switched to partial diffraction efficiencies in order to extend the depth of available attenuation, if desired.

[0097] Shown in Figures ~~2a-2b~~10a-10b are pictorial, schematic representations of other embodiments of a variable optical attenuator of this invention. Fig. ~~2a~~10a shows an embodiment of a variable optical attenuator of this invention including a polarization separating sub-system 430, a switchable volume diffraction grating ~~110~~510, a static grating ~~120~~520, and a polarization recombining sub-system 450. The static grating ~~120~~520 can be, in one embodiment, a volume diffraction grating that is non-switchable.

[0098] The configurations of the embodiments shown in Figs. ~~2a~~10a and ~~2b~~10b typically operate as "normally-on" configurations. Again, this nomenclature is based on the assumption of using common switched gratings ~~110~~510 that are diffracting with no switching power applied, and non-diffracting when power is applied, The input optical beam 420 is a beam of

arbitrary polarization. The beam 420 is received by (enters) a polarization separating sub-system 430 (also referred to as a polarization diversity filter, or a compensator), which separates the input optical beam 420 into a first optical beam of a first polarization and a second optical beam of a second polarization, the second polarization being distinct from the first polarization. The polarization separating sub-system 430 is capable of emitting a first emitted optical beam of the first polarization and a second emitted optical beam of the first polarization. The emitted first and emitted second optical beams constitute an input channel of the first polarization.

[0099] In the normally-on configuration of Fig. ~~2a~~10a, the input channel encounters the switchable volume diffraction grating ~~110~~510 and is diffracted into the first-order when no voltage is applied across the grating. The input channel is then diffracted to the polarization recombining sub-system 450 by the static grating ~~120~~520. The diffracted channel includes a first transmitted optical beam of the first polarization and a second transmitted optical beam of the first polarization. A polarization recombining sub-system 450 is optically disposed to receive the first transmitted optical beam of the first polarization and the second transmitted optical beam of the first polarization and is capable of recombining the first transmitted optical beam of the first polarization and the second transmitted optical beam of the first polarization into a final output beam 460 of combined polarization. When an appropriate voltage (in the electrical switching embodiment) is applied across the switchable volume diffraction grating ~~110~~510, the input channel is transmitted (not diffracted) through switchable grating ~~110~~510 and is not coupled into the output at

the location shown in Fig. ~~2a~~10a. Since the diffraction efficiency of a switchable transmission volume grating varies continuously with applied voltage, varying the voltage of the control signal on switchable grating ~~110~~510 varies the percentage of the optical power of the input channel that is diffracted to the output 460, and therefore the output optical power of the VOA of this invention is continuously variable.

[00100] It should be noted that embodiments operating in the normally-off configuration are also possible. ~~.~~For example, if a switchable grating that is transmitting with no applied power (and diffracting with applied power) is used as grating ~~110~~510 in Figure ~~2a~~10a, the configuration will operate as normally-off.

[00101] It should be noted that since the switchable gratings can be optically switched, electrically switched, polarization switched, or switched based on other mechanisms, the switching controls (voltage, or optical or polarization control) are means for varying the diffraction efficiency of the switchable gratings.

[00102] Shown in Fig. ~~2b~~10b is an embodiment of the VOA system of this invention in which the input channel encounters the static grating ~~120~~520first and then encounters the switchable transmission volume grating ~~110~~510. The operation of the VOA system of this invention shown in Fig. ~~2b~~10b is analogous to that of the VOA system of this invention in Fig. ~~2a~~10a.

[00103] It should also be noted that switchable gratings in addition to switchable gratings ~~110~~510 could replace the static grating ~~120~~520 in Figures ~~2a~~10a and ~~2b~~10b. This allows, for example, for additional degrees of attenuation of the input signal if required. For example, consider the configuration of Figure ~~2a~~10a. If static grating ~~120~~520 is replaced by a

switchable grating, it can be set to a diffracting state and the operation of the VOA is as described above. However, if it is desired to heavily attenuate the output channel, both the switchable grating replacing static grating ~~120~~520 and switchable grating ~~110~~510 can be switched to non-diffracting states. In such a configuration, if the switchable gratings give a 25 dB contrast between diffracting and non-diffracting states, switching both gratings can provide a roughly 50 dB optical attenuation level to the output. This approximately doubles the dBs of attenuation available by switching only a single grating.

[00104] Figure ~~3~~11 shows a pictorial, schematic representation of an embodiment ~~200~~600 of a 1X2 optical switch of this invention. The embodiment ~~200~~600 of the 1X2 optical switch of this invention includes a polarization separating sub-system 430, a switchable volume diffraction grating ~~110~~510, a static grating ~~210~~610, and a polarization recombining sub-system 450. The static grating ~~210~~610 includes a transparent region ~~220~~620.

[00105] As in the embodiment of Fig. ~~2a~~10a, the input optical beam 420 is a beam of arbitrary polarization. The input beam 420 is received by (enters) the polarization separating sub-system 430 (also referred to as a polarization diversity filter, or a compensator), which separates the input optical beam 420 into a first optical beam of a first polarization and a second optical beam of a second polarization, the second polarization being distinct from the first polarization. The polarization separating sub-system 430 is capable of emitting a first emitted optical beam of the first polarization and a second emitted optical beam of the first polarization. The emitted first and

emitted second optical beams constitute an input channel of the first polarization.

[00106] During operation of the 1X2 switch ~~200~~600 of this invention, the input channel is incident on the switchable volume diffraction grating ~~110~~510. The switchable grating ~~110~~510 is set to either fully diffracting, fully transmitting, or some intermediate state of diffraction efficiency by the control ~~115~~515 (voltage, in one embodiment). The fraction of the input channel that is undiffracted by switchable grating ~~110~~510 is transmitted through switched grating ~~110~~510 as transmitted beams ~~215~~615. These beams are then incident on the transparent region ~~220~~620 of static grating ~~210~~610, where they are again transmitted as beams ~~215~~615.

[00107] Similarly the fraction of the input channel that is diffracted by switchable grating ~~110~~510 propagates as diffracted beams ~~225~~625. These diffracted beams ~~225~~625 are then incident on the static diffraction grating ~~210~~610 and are diffracted by grating ~~210~~610.

[00108] A polarization recombining sub-system 450 is optically disposed to receive the transmitted beams ~~215~~615 and the diffracted beams ~~225~~625. The transmitted beams ~~215~~615 and the diffracted beams ~~225~~625 each includes a first optical beam of the first polarization and a second optical beam of the first polarization. The polarization recombining sub-system 450 is capable of recombining the first optical beam of the first polarization and the second optical beam of the first polarization for each of beams ~~215~~615 and ~~225~~625 into two final output beams ~~260~~660 and ~~250~~650, respectively, of combined polarization. In one embodiment the 1X2 switch ~~200~~600 of this invention includes two output beam ports ~~230~~630, ~~240~~640 (for

example, two collimator/single mode fiber combinations). The two output beam ports ~~230~~630, ~~240~~640 receive two final output beams ~~250~~650, ~~260~~660 of combined polarization.

[00109] Since the diffraction efficiency of switchable diffraction grating ~~110~~510 can be varied in a continuously varying manner using control ~~115~~515 (electrical in one embodiment), variable amounts of the optical power in input 20 can be switched among outputs ~~230~~630 and ~~240~~640. This also includes the cases where substantially all of the input power is switched to either output ~~230~~630 or to output ~~240~~640. For the case where it is desired to switch all of the incident power to only one of the outputs at a time, it may be advantageous to replace static grating ~~210~~610 and transparent region ~~220~~620 by a single switched grating. In such a case, when it is desired to send all of the power to output ~~230~~630, both switchable gratings could be set to fully diffracting. This would not only route substantially all of the power to the desired output, but any input signal leaking through the first switchable grating as undiffracted light, would be additionally attenuated from being crosstalk in the output ~~240~~640 by diffraction from the second switchable grating. Similarly, when setting the switch to direct substantially all of the power to the output ~~240~~640, both switched gratings would be set non-diffracting. This would not only direct substantially all of the input power to the output ~~240~~640, but any input signal leaking through the first grating as diffracted light will be further attenuated from being crosstalk in the output ~~250~~650 by the non-diffracting second grating.

[00110] If the embodiment of the switchable diffraction grating is not polarization sensitive, i.e., if it diffracts

with the same diffraction efficiency regardless of the state of the incident polarization, then the polarization separating sub-systems 430 and the polarization combining sub-systems 450 of the configurations of Figures ~~1-3~~9-11 are not necessary. Similarly, if the embodiment of the switchable diffraction gratings switch a single polarization, but that polarization is the only one incident on the system, then the polarization separating sub-systems 430 and the polarization combining sub-systems 450 of the configurations of Figures ~~1-3~~9-11 are not necessary.

[00111] For example, if the embodiment of the switchable volume diffraction grating is such that beams of electromagnetic radiation with polarization in a predetermined plane of polarization are diffracted by the enabled grating and if the input beam 420 has a polarization in that predetermined plane of polarization, the polarization separating sub-system 430 and the polarization recombining sub-system 450 are not necessary and can be omitted from the system of this invention. Systems of this invention in which the input beam 420 has a polarization in the predetermined plane of polarization in which the switchable volume diffraction grating ~~110~~510 preferably operates are shown in Figs. ~~4a~~12a, ~~4b~~12b and ~~5~~13.

[00112] During operation of the embodiment of Fig. ~~4a~~12a, when the switchable volume diffraction grating ~~320~~720 is enabled (either by its initial state or by a switching control such as a voltage), the input beam encounters the switchable volume diffraction grating ~~320~~720 and is diffracted. The diffracted beam is then further diffracted by the static grating 330 resulting in output beam ~~340~~740. Since the diffraction efficiency of the switchable transmission volume grating varies

continuously with applied voltage (switching control), the percentage of the optical power of the input channel that is diffracted to the output ~~340~~740, and therefore the output optical power of the VOA of this invention, is continuously variable.

[00113] During operation of the embodiment of Fig. ~~4b~~12b, when the switchable volume diffraction grating ~~320~~720 is enabled (either by its initial state or by a switching control such as a voltage), the input beam ~~310~~710 encounters the static grating ~~330~~730 and is diffracted. The diffracted beam then encounters the switchable volume diffraction grating ~~320~~720 and is diffracted resulting in output beam ~~340~~740.

[00114] Figure ~~5~~13 shows an embodiment ~~400~~700 of the 1X2 switch of this invention in which the input beam ~~310~~710 has a polarization in the predetermined plane of polarization in which the switchable volume diffraction grating ~~320~~720 preferably operates. During operation of the embodiment ~~400~~800 of Fig. ~~5~~13, when the switchable volume diffraction grating ~~320~~720 is enabled (either by its initial state or by a switching control such as a voltage), the input beam encounters the switchable volume diffraction grating ~~320~~720 and its optical power is divided among transmitted beam ~~410~~810 and diffracted beam ~~420~~820. Diffracted beam ~~420~~820 is further diffracted by the static grating ~~360~~760. Transmitted beam ~~410~~810 is further diffracted by the static grating ~~360~~760. Transmitted beam ~~410~~810 is transmitted through the transparent region ~~370~~770. The diffracted beam and the transmitted beam comprise the output beams ~~440~~840, ~~430~~830. The optical power in input beam ~~310~~710 is variably divided into the two outputs ~~430~~830 and ~~440~~840 by setting the switchable grating ~~320~~720 to a predetermined

diffraction efficiency which is determined by the switching control ~~315~~715 (voltage, in one embodiment). The switchable grating ~~320~~720 is set to either substantially fully diffracting, substantially fully transmitting, or some intermediate state of diffraction efficiency by the control ~~315~~715 (voltage, in one embodiment). It should be noted that by setting the switchable grating ~~320~~720 to either substantially fully diffracting or substantially fully transmitting, the transmitted beam can be substantially absent or the diffracted beam can be substantially absent.

[00115] It should be noted that, in the embodiments of Figs. ~~4a~~12a, ~~4b~~12b, and ~~5~~13, the static grating may be, but is not limited to, a volume diffraction grating or may be replaced by a switchable volume diffraction grating.

[00116] It should also be noted that the switchable gratings of this invention may be volume holographic gratings, but may also be switchable gratings of other types including switchable surface relief gratings.

[00117] Although the invention has been described with respect to various embodiments, it should be realized this invention is also capable of a wide variety of further and other embodiments within the spirit and scope of the appended claims.

[00118] What is claimed is:

Samuel C. Barden, James A. Arns, and Willis S. Colbur, *Volume-phase holographic gratings and their potential for astronomical applications,* Proceedings SPIE vol. 3355, "Optical Astronomical Instrumentation" pp. 866-876, 1998 (a copy of which is was submitted with the Response to the Final Office Action filed on August 16, 2006)

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Volume-phase holographic gratings and their potential for astronomical applications

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ABSTRACT

A diffraction grating technology based upon volume-phase holograms shows promise of enhanced performance for many applications in astronomical spectroscopy over classical surface-relief grating technology. We present a discussion of the underlying physics of a volume-phase grating, give some theoretical performance characteristics, present performance data for a real volume-phase grating, and discuss some potential applications for this grating technology.

Keywords: diffraction gratings, holographic gratings, spectrographs, astronomical instruments

1. INTRODUCTION

In recent years, a new type of grating has been developed using holographic techniques[1]. Rather than being diffracted by surface-relief structures as in a surface grating (generated either by diamond ruling or by a holographic exposure of a photoresist layer), the light undergoes Bragg diffraction as it passes through the volume of a thin layer in which the refractive index is modulated. These volume-phase (VP) holographic gratings show promise for improved performance over classical, low-order, surface-relief gratings in the following areas:

- The "blaze" or efficiency envelope is governed by Bragg diffraction and can be tuned by adjustment of the grating angle for different wavelengths or diffraction orders.
- They can have high diffraction efficiencies approaching 100% for high line density (600 to 6000 l/mm), high dispersion transmission gratings with relatively low dependence on polarization angle.
- The technology can likely produce very large grating sizes (at least 600 by 850 mm).
- Complex grating structures can be produced to minimize optical elements in some spectrograph configurations, simplifying spectrograph design and enhancing spectrograph efficiency.
- The grating is sandwiched between two substrates providing an environmentally stable device which is robust, can be cleaned, can have anti-reflection coatings applied, and is capable of long lifetimes without degradation.
- Grating customization is relatively straightforward as each grating is an original rather than a replica of an expensively ruled master.
- Both transmission and reflection grating geometries are possible.

VP grating technology can improve both the versatility and the efficiency of optical astronomical spectrographs.

A brief overview of the underlying physics is presented and followed by a discussion of both theoretical and actual grating performance. We close with a discussion on many of the various possibilities provided by volume-phase gratings.

2. VOLUME-PHASE GRATING PHYSICS

The diffracting mechanism in VP gratings arises from modulations in the refractive index in the form of fringe planes running parallel to each other through the depth of the grating material and oriented so that the fringes terminate at the surfaces of the volume[2,3]. Figure 1 schematically displays the structure and geometry of four types of VP gratings.

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* Operated by the Association of Universities for Research in Astronomy, Inc. (AURA) under cooperative agreement with the National Science Foundation.

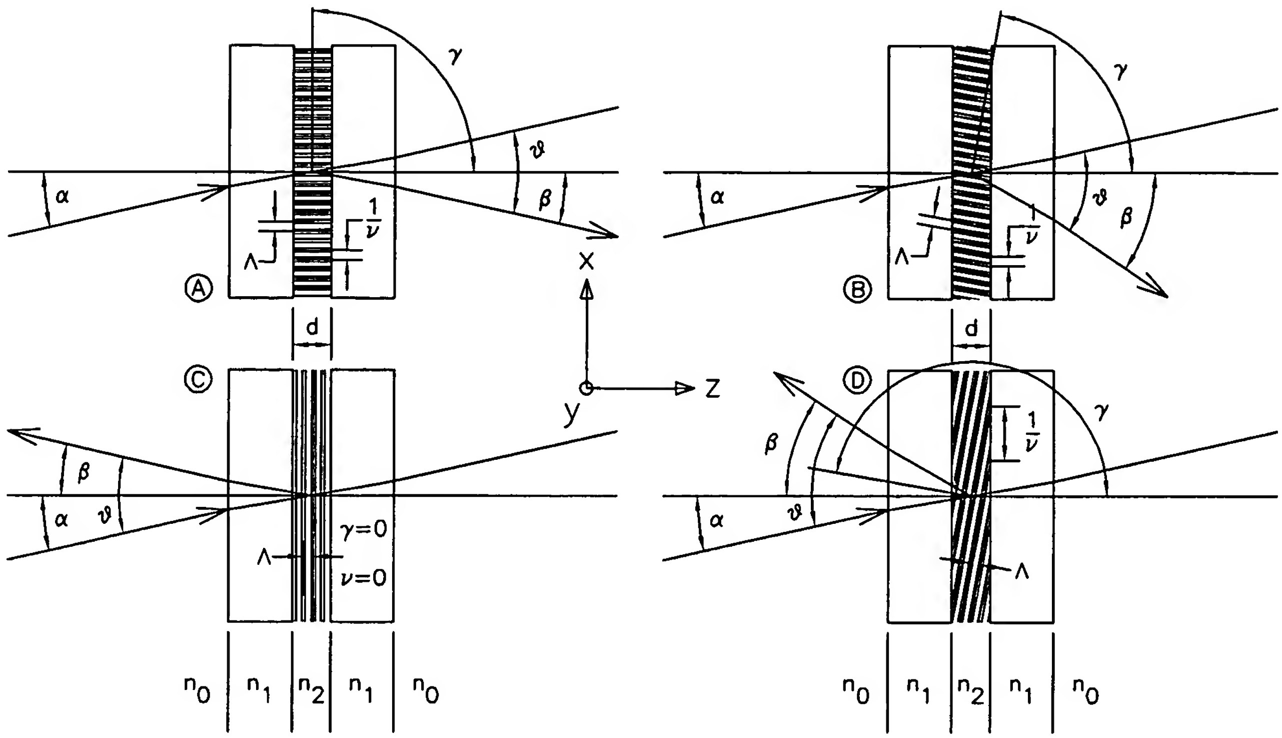

Figure 1. *Some possible VP grating configurations showing Bragg condition diffraction.* ***A.*** *Transmission grating with fringes perpendicular (γ = 90 degrees) to the grating surface (unslanted fringes). In this case the magnitude of α equals that of β for the Bragg condition.* ***B.*** *Transmission grating with tilted fringes.* ***C.*** *Reflection grating with fringes parallel (γ = 0) to the grating surface. This grating does not disperse the light since ν is zero. Again, the magnitude of α and β are equivalent for the Bragg condition.* ***D.*** *Reflection grating with tilted fringes.*

The spacing ($1/\nu$) of the fringe planes as they intersect the surface of a VP grating define the grating dispersion, diffracting light according to the standard grating equation in the same manner as a classical surface-relief grating. The grating equation for a transmissive VP grating can be represented by

$$m\nu\lambda = \sin(\alpha) - \sin(\beta) \tag{1}$$

where m is the order of diffraction, ν is the grating frequency, λ is the wavelength of light in free space, α is the angle of incidence in air, and β is the angle of diffraction in air. Light traversing a VP grating, however, is also affected by interaction with the fringes as it travels through the bulk or volume of the grating material. The depth of the grating volume, the intensity or contrast of the fringe structure, and the angular and spectral relationship of the incident light to the Bragg condition determine how much light goes into which order. The Bragg condition for a plane, parallel grating with fringes that are normal to the grating surface (the case shown in Figure 1a) is given by

$$m\lambda = \Lambda\, 2\, n_2 \sin(\alpha_{2B}) \tag{2}$$

where Λ is the fringe spacing of the grating equal to $1/\nu$ for fringe planes orthogonal to the grating surface, and α_{2B} is the Bragg angle in the grating medium. The Bragg condition is met when m is an integer and the wavelength and fringe spacing are such that the angles of incidence and diffraction are equal and opposite (with respect to the surface normal). The formulation of the Bragg condition for slanted fringes is slightly more complex, but in that case the angles of incidence and diffraction are symmetric within the grating medium about the fringe planes. Light illuminating the grating at angles significantly outside of the Bragg condition may pass through the grating without being diffracted. However, near the angle at which the Bragg condition is satisfied there is a range of angles for which light will still be efficiently diffracted; these

angles can be thought of as falling within a Bragg envelope and having an angular bandwidth as shown by the sample curve in Figure 2a. Similarly, the wavelength that satisfies the Bragg condition is called the Bragg wavelength, and again there is a Bragg envelope of wavelengths about the Bragg wavelength that are diffracted efficiently as shown in Figure 2b. Wavelengths that are significantly outside the spectral bandwidth may pass through the grating undiffracted. It is this selective aspect which allows these gratings to be tuned for different orders of diffraction and or wavelengths by tilting the grating with respect to the incident beam of light.

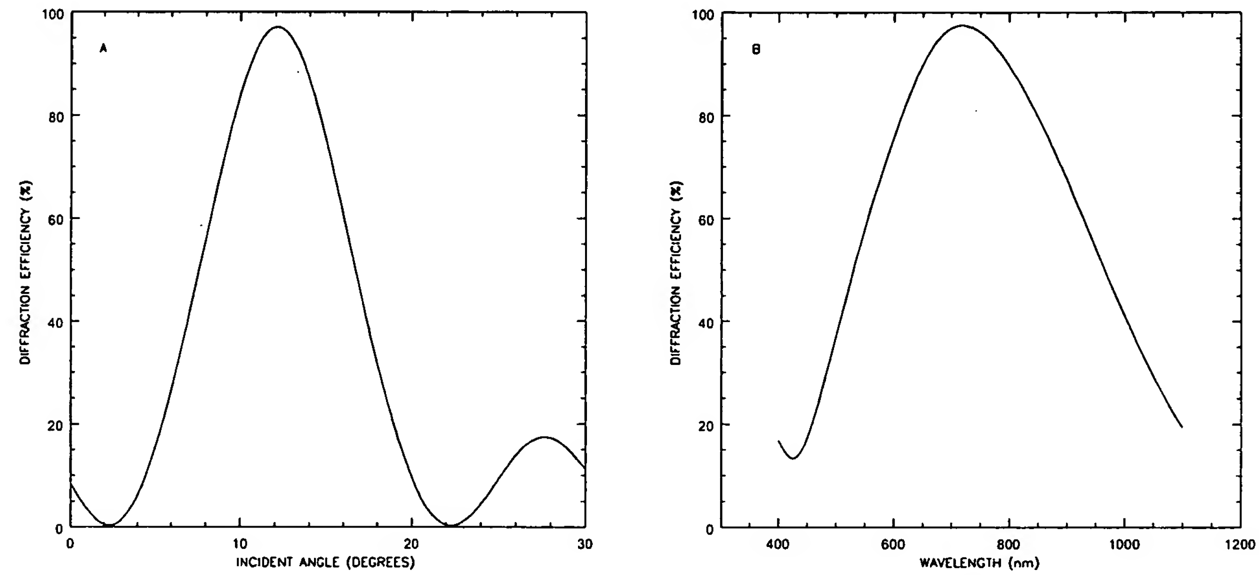

Figure 2. *The angular and wavelength bandwidth Bragg envelopes for a theoretical 600 l/mm grating designed for 1st order operation at 700 nm.* ***A.*** *Angular bandwidth Bragg envelope.* ***B.*** *Wavelength bandwidth Bragg envelope.*

Figure 1 shows the grating parameters (α, β, γ, θ, Λ, d, n_2) which, along with the amplitude of the index of refraction modulation (Δn_2), determine the grating performance. The index of refraction, n_2, for the grating itself is the average value of the modulated refractive index, $n_2(x,z)$, and is approximately represented by

$$n_2(x,z) = n_2 + \Delta n_2 \cos[(2\pi/\Lambda)(x \sin(\gamma) + z \cos(\gamma))] \qquad (3)$$

for the case of either slanted or unslanted fringes where Δn_2 is the semi-amplitude of the variation in the index of refraction within the grating volume. The substrate index of refraction is given by n_1 and the refractive index for air is n_0 (assumed to be equal to 1).

Volume-phase gratings can be analyzed by means of either a rigorous coupled-wave analysis[4,5] or a modal analysis[6]; the two approaches are exact and can be shown to be equivalent[7]. In their most rigorous forms, these approaches require computer-derived solutions. Using a simplified coupled-wave analysis that includes only zeroth and first order diffraction, Kogelnik[8] developed a set of closed-form equations that are sufficiently accurate in many cases, and that are widely used in the field of volume holography.

The diffraction efficiency, spectral bandwidth, and angular bandwidth are influenced by the Bragg condition and are functions of the intensity of the grating modulations (Δn_2) and the thickness (d) of the grating volume[4,5,8]. In general, a VP grating with a wide spectral bandpass has a lower peak diffraction efficiency than a grating with a narrower bandpass. For transmission gratings, the peak diffraction efficiency at the Bragg condition is a function of both the grating thickness and modulation intensity. For orthogonal fringe (unslanted) plane gratings the efficiency η at the 1st order Bragg condition is[8]

$$\eta = \sin^2[\pi \, \Delta n_2 \, d \, / \, (\lambda \cos(\alpha_{2B}))] \qquad (4)$$

where α_{2B} is the angle within the grating material (where $n = n_2$) given by the relation

$$\sin(\alpha_{2B}) = (n_0 / n_2)\sin(\alpha). \tag{5}$$

The 1st order spectral bandwidth and angular bandwidth for unslanted, transmission gratings are approximated by[8]

$$\Delta\lambda_{FWHM} / \lambda \sim (\Lambda/d)\cot(\alpha_{2B}), \tag{6}$$

$$\Delta\alpha_{FWHM} \sim \Lambda/d \tag{7}$$

where $\Delta\alpha_{FWHM}$ is in radians. The challenge in VP grating fabrication is to produce a grating with appropriate thickness and refractive index modulation to provide the desired peak efficiency and bandwidth performance.

Polarization dependence in VP gratings is dominated by a reduced coupling constant for parallel polarization of light with respect to the plane of incidence (p or TM polarization)[8], whereby Equation (4) becomes

$$\eta = \sin^2\{[\pi\,\Delta n_2\, d / (\lambda\cos(\alpha_{2B}))]\cos(\theta_2)\} \tag{8}$$

where θ_2 is the angle within the medium between the incident (α_{2B}) and diffracted (β_2) wavefronts. When the angle between the incident and diffracted waves within the grating equals 90°, the diffraction efficiency for this polarization state goes to zero. Polarization dependencies can be minimized as long as this condition is avoided.

3. GRATING FABRICATION

The VP gratings in this study are fabricated in dichromated gelatin. A thin film of sensitized gelatin is deposited onto a glass substrate and exposed in a holographic exposure system to record an interferometrically produced wave pattern of the desired fringe frequency and orientation. Wet processing transforms the exposed fringes into refractive index modulations within the gelatin. Once the desired grating parameters have been achieved, a cover glass is laminated over the gelatin surface. The substrate may be any glass material; typical optical glasses used are BK7 and fused silica. Anti-reflection coatings can be applied to the substrates to reduce reflection losses. It is also possible to use prisms and plano-convex or plano-concave lenses in the grating assembly.

Contrary to the statement that dichromated gelatin "is not an attractive candidate for high accuracy, because it is difficult to process gelatin in such a way that the modulation pattern is accurately reproduced after a wet-dry processing cycle"[9], this material has been used extensively in holographic components for over twenty five years with a proven record of producing high quality diffraction elements with high diffraction efficiency, high clarity, low scatter, low absorption, and long lifetime when properly treated in the fabrication process and adequately protected against degrading environmental conditions[10,11,12]. Due to the hygroscopic nature of the gelatin, a protective cover glass is required to prevent water vapor from affecting the sensitive film and to protect the grating from contaminants. Properly sealed dichromated gelatin holograms can have lifetimes of at least 20 years if they are given reasonable care and handling. Their application as head-up display components in military aircraft show that elements fabricated in this manner can withstand considerable humidity and temperature extremes.

Figure 3 shows the transmission behavior of dichromated gelatin between 300 and 3000 nm. It is apparent that the material may have a useful spectral range from 300 nm to 2.8 μm. VP gratings are currently and routinely fabricated for use between 400 nm and 1.5 μm. Typical values of n_2, Δn_2, and d obtained with dichromated gelatin gratings are 1.5, 0.02 to 0.10, and 4 to 20 μm, respectively. Line densities (ν) range from 300 to 6000 l/mm.

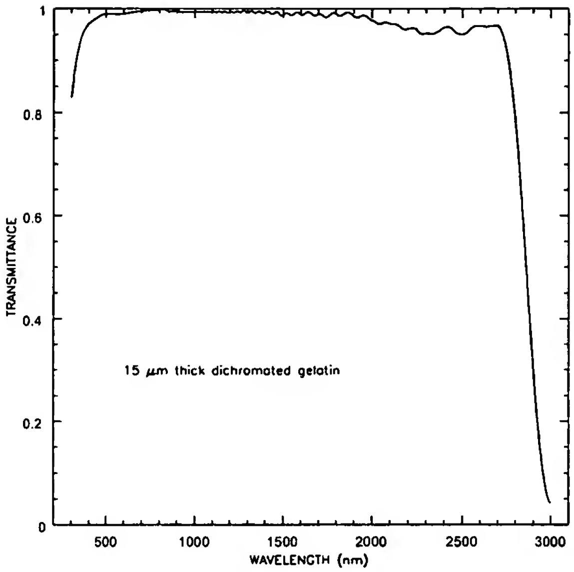

Figure 3. *The transmittance as a function of wavelength for a 15 μm thick layer of uniformly exposed and processed dichromated gelatin.*

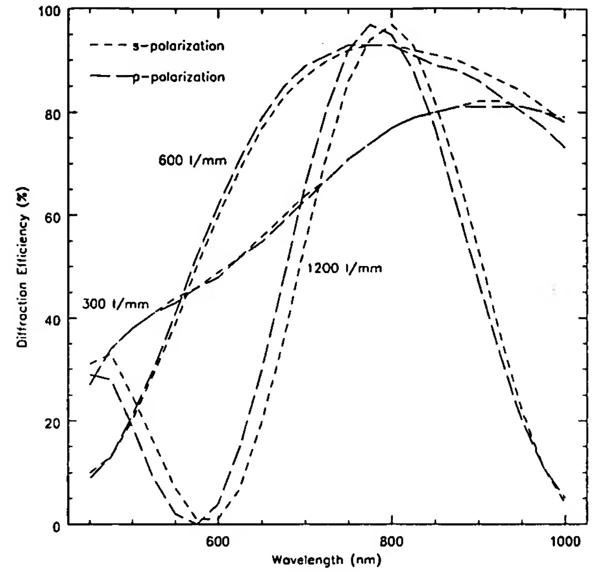

Figure 4. *Rigorous coupled-wave prediction for the diffraction efficiency of three different gratings designed for first order operation at 790 nm. Both s and p polarization states are shown. Material and reflection losses are not included.*

4. GRATING PERFORMANCE

The high diffraction efficiency of dichromated gelatin and the characteristics of Bragg diffraction give the potential for very high efficiency dispersers. Figure 4 shows the theoretically achievable diffraction efficiencies derived through rigorous coupled-wave analysis[4] of three different transmissive VP gratings designed for operation at 790 nm. Notice that the peak diffraction efficiency and bandwidth are traded off against each other. Polarization effects are not very significant. For comparison, a reflective, surface-relief grating blazed at 790 nm will only have a theoretical peak efficiency of about 80% in unpolarized light due to the major dependency of efficiency on the angle of polarization[9].

A 600 l/mm VP grating (HG-700-12) was produced by Kaiser Optical Systems, Inc. (KOSI) for evaluation at the National Optical Astronomy Observatories (NOAO) as part of an effort to design a new technology, high efficiency spectrograph. The grating was designed for optimal efficiency at 700 nm with a bandwidth covering the spectral region spanning 500 to 900 nm in the first order of diffraction. Peak efficiency was specified at 70 to 80% with greater than 50% efficiency at 500 and 900 nm. The grating modulations are perpendicular to the surface of the grating substrate, so the Bragg condition is met when the incident and diffracted angles are the same magnitude.

The absolute efficiency for unpolarized light was measured at NOAO at 400, 500, 633, 700, 800, and 900 nm as a function of incident angle and of diffracted angle. When the grating is illuminated at zero degrees incidence, the majority of the light passes undiffracted into the zeroth order. As the angle of incidence is increased, the level of diffraction increases. Peak diffraction into first order at 700 nm is achieved when the incident angle is about 12 degrees (the first order Bragg condition). At an angle of incidence equal to about 25 degrees, 700 nm meets the Bragg condition for second order diffraction. Figure 5 displays the absolute efficiency of the unpolarized light transmitted and diffracted by the grating at a wavelength of 700 nm as a function of angle of incidence and order of diffraction. A peak efficiency of nearly 80% is achieved for first order diffraction. In comparison with a comparable theoretical VP grating (see Figure 4), this grating is about 10% lower than might be expected. This is attributable to the inclusion of reflective and other material losses in the

measurements of Figure 5 and due to some residual uncertainty in the holographic process which optimizes the grating thickness and the index modulation. Future process refinements will lead to an improved capability of producing gratings with efficiencies that more closely approach the theoretical limits.

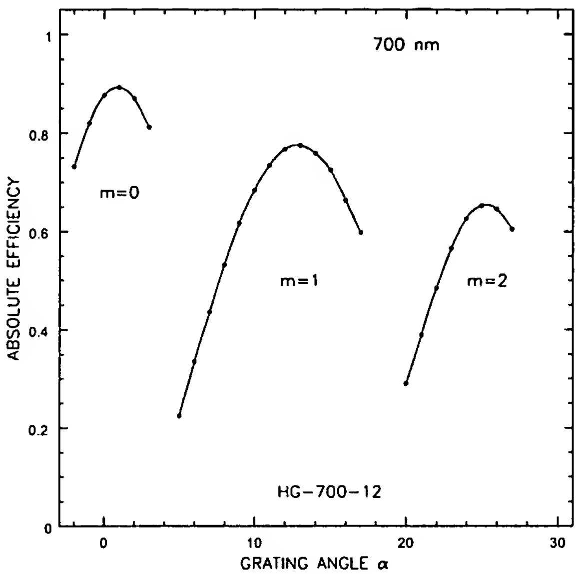

Figure 5. *Absolute efficiency of the 600 l/mm VP grating for unpolarized light as a function of incident angle and diffracted order (m=0,1,2) for 700 nm. Material and reflective losses are included.*

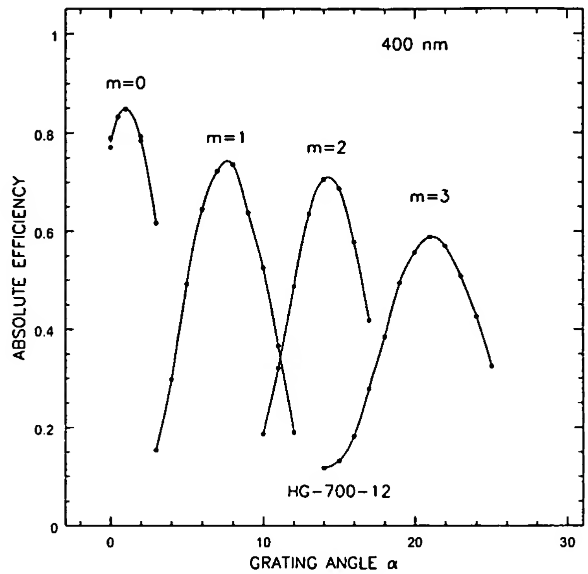

Figure 6. *Absolute efficiency of the 600 l/mm VP grating in unpolarized light at 400 nm for diffraction orders m=0, 1, 2, and 3. Material and reflective losses are included.*

Comparable surface-relief gratings in use at Kitt Peak National Observatory (KPNO) give 70% efficiency at 700 nm in first order (Bausch and Lomb grating 420, 600 l/mm blazed at 750 nm) and 42% for 700 nm in 2nd order (Bausch and Lomb grating 450, 632 l/mm blazed at 1100 nm in 1st order and which has a peak efficiency in 2nd order of 50% at 550 nm). The VP grating shows good performance at the design wavelength in comparison with these other gratings. It also shows superior performance for the 2nd order of diffraction, a region in which it was not specifically designed to function!

At 400 nm, the VP grating still shows excellent performance when aligned for Bragg diffraction at that wavelength for 1st, 2nd, and 3rd order diffraction (7, 14.2, and 21.6 degrees respectively). Figure 6 displays the measured absolute efficiencies for diffraction at 400 nm.

Comparable surface gratings at KPNO are inferior to this grating with only 50% efficiency for 1st order diffraction by a grating originally ruled at KPNO (KPC007, 632 l/mm blazed at 520 nm), 55% efficiency for 2nd order diffraction by another grating ruled at KPNO (KPC22b, 632 l/mm blazed at 850 nm in 1st order), and 40% in 2nd order by a Bausch and Lomb grating (Bausch and Lomb 450, 632 l/mm, blazed at 1100 nm in 1st order). The 3rd order diffraction efficiencies for any of the gratings at KPNO were unavailable for comparison.

The strong performance in higher orders of diffraction for this grating is intriguing and has prompted the authors to further explore the feasibility of high order diffraction VP gratings. Very little research has been conducted in this area since the typical customer for volume holographic devices does not want high order diffraction. As a result, little or no effort has been expended to optimize the performance of a high order VP grating.

The bandwidth of the grating was determined by measuring the efficiency for each wavelength at a specific grating angle, or angle of incidence. Figure 7 shows the equivalent of the "blaze" function as a function of grating tilt for 1st order

diffraction. Tilts of 11 to 12 degrees give the best overall efficiency across the design spectral range of 500 to 900 nm with greater than 55% efficiency and a peak efficiency of nearly 80% between 600 and 700 nm. Note that the grating also makes an excellent, 1st order, blue grating when used at a grating tilt of 8 to 10 degrees. Comparison with the Bausch and Lomb 420 grating (600 l/mm, blazed at 800 nm) at KPNO (Figure 8) shows that the VP grating is about 5 to 10% more efficient across the entire design spectral range.

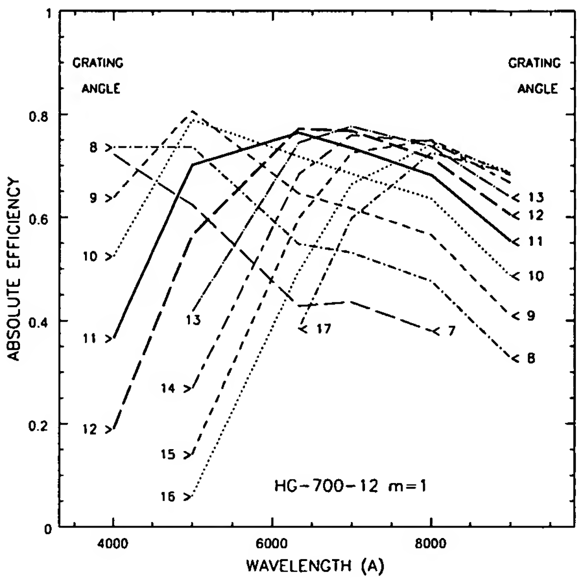

Figure 7. *Efficiency envelope of the 600 l/mm VP grating as a function of incident angle for first order diffraction. Grating tilts of 11 and 12 degrees give the best overall efficiency in the design bandwidth from 500 to 900 nm.*

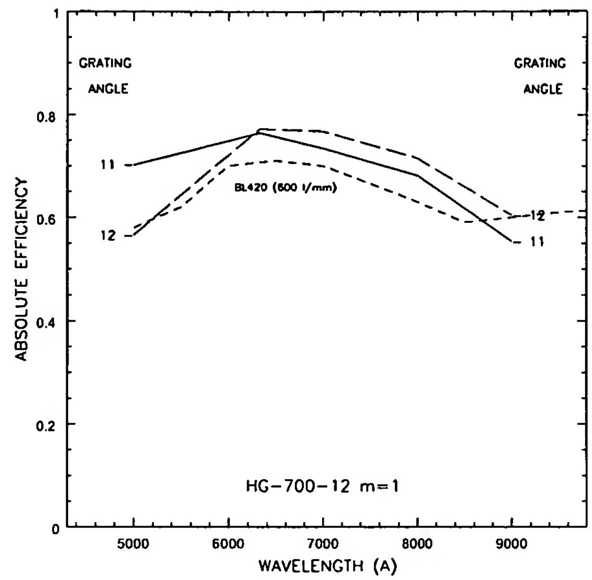

Figure 8. *Comparison of the 600 l/mm VP grating at grating tilts of 11 and 12 degrees to a diamond ruled, 600 l/mm, reflection grating blazed at 800 nm (Bausch and Lomb 420).*

A simple, on-sky test was made with the test VP grating at the KPNO 2.1 meter telescope using a fiber optic feed onto an optical bench. The 22 meter long, 200 μm diameter fiber optic cable fed light from the telescope to a 40 mm diameter achromatic doublet collimating lens. An OG515 high-pass filter was used to filter out 2nd order contamination. A second 40 mm diameter achromatic doublet lens was used to image the light dispersed by the test grating onto a 2048 Tektronix CCD binned 2 by 2 to get 48 μm pixels. The system was first aligned at 12 degrees for first order diffraction from the grating. A standard star was observed and the count rate transformed into a flux rate. The total system (telescope, fiber aperture, fiber, lenses, grating, and detector) efficiency at 670 nm was measured to be 17.0%. The system was then reconfigured to 25 degrees for 2nd order diffraction at the same wavelength and another spectrum obtained. System efficiency was again measured to be 17.2% for 2nd order. Independent determination of the fiber, telescope, aperture, and detector efficiency showed that the two lenses plus grating were 60% efficient in the R band (144 nm bandwidth at 647 nm) in the first order of diffraction. This agrees remarkably well with the laboratory measurements especially given the uncertainty in the atmospheric seeing which was estimated to be variable by about 30% during the course of the observations. Figure 9 displays the spectra for both 1st and 2nd order configurations. Note that the shape of the spectra are dominated by the cutoff filter at 515 nm and by vignetting of the dispersed spectrum by the imaging lens (most notable in the 2nd order spectrum) along with the diminishing quantum efficiency of the CCD detector in the red portion of the spectrum.

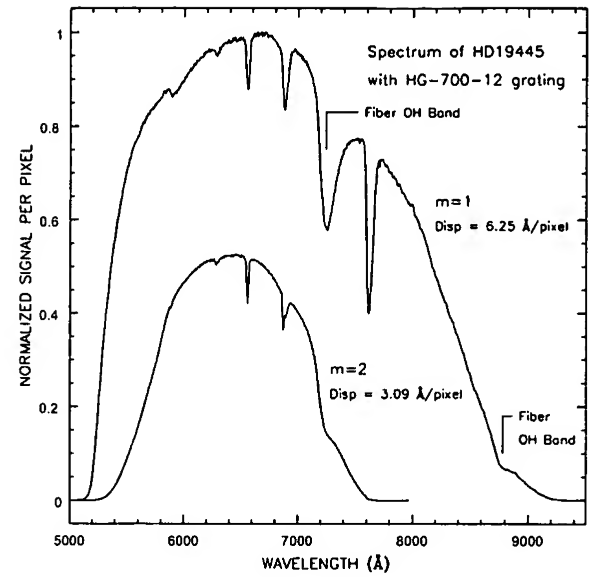

Figure 9. *Stellar spectra obtained in first and second orders of diffraction.. The units of the ordinate axis were selected to remove confusion of the two curves but give the false impression that the 2nd order spectrum has a factor of two lower signal.*

5. POSSIBILITIES

5.1 Transmission gratings

The blazing for surface-relief, transmission gratings, particularly in the red portion of the optical spectrum, can be difficult and sometimes impossible due to the large facet angles and grating depths required. This is particularly true for high dispersion gratings (rulings greater than 600 l/mm for unimmersed gratings)[9]. Inclusion of a prism, making the grating into a grism, allows surface rulings of up to 1200 l/mm before production gets difficult. Many of these restrictions in performance arise from the presence of the surface facets that make the grating. Total internal reflection becomes an issue in the production of such gratings as well as complications in the ability to replicate a surface grating with large and steep grooves.

VP gratings are not limited by either total internal reflection on steep grooves or by the inability to replicate a grating with deep groves since the grating mechanism arises from refractive index modulations rather than surface discontinuities. As such, VP gratings can be fabricated as transmission gratings with line densities of up to and greater than 6000 l/mm. The peak efficiency of a transmission VP grating can also exceed the peak limits of a transmissive surface-relief grating as a consequence of the different diffraction mechanism.

5.2 Reflection gratings

As shown in Figure 1, a reflection VP grating can be produced by creating a sufficient tilt in the holographic fringes with respect to the surfaces of the grating. The peak diffraction efficiency of a reflective VP grating can be quite high but in many cases the bandwidth may be narrower than desired. Some studies have shown that the bandwidth can be increased by modifications in the hologram processing[14,15].

Most reflective VP holographic devices are currently designed to be non-dispersive. There appears to be little activity in the study or production of reflective VP gratings which disperse light into diffraction orders other than zero. Further study of dispersive reflective gratings, however, is warranted and desired. Other than potentially superior performance, the development of large, reflective VP gratings will allow drop-in replacements for many current astronomical spectrographs utilizing reflective surface-relief gratings.

5.3 Grating customization

One of the most frustrating aspects of currently available gratings is the lack of a sufficient sampling in the parameter space of peak efficiency and dispersion, especially with regards to large, astronomical gratings. In order to acquire a grating of desired properties, one must compromise to the closest available catalog grating or have a master grating generated. Quite often, the closest available grating is poorly matched to what is actually desired and large, custom, master, surface-relief gratings are expensive and take a considerable amount of time to generate.

VP holographic gratings are typically not replicas (though there are processes which could replicate VP gratings from a single master[13]) and are relatively straightforward to produce. As such, customization of the grating parameters is more easily attained without a major expenditure in cost or time.

5.4 Complex grating structures

The holographic nature of these gratings allows the stacking of holograms to make a variety of complex grating structures[16,17]. A single grating assembly might contain a second grating with the fringes perpendicular to the first in order to provide cross-dispersion. A second concept is a double grating which disperses light of two different wavelengths into the same angle of diffraction. For example, it would be possible to create a complex grating in which Hα light meets the Bragg condition of the first hologram but not the second and Hβ light satisfies the Bragg condition of the second but not the first VP grating. The correct ratio of line densities in the two gratings would direct both Hα and Hβ into the same angle of diffraction for simultaneous detection by a single detector. A third concept would be a dual grating that divides the light at different wavelengths into different paths to function as a dispersive beam splitter.

5.5 Large gratings

VP gratings are currently fabricated by KOSI and utilized in their line of Raman spectrographs[18]. Although they currently only fabricate gratings of up to 75 by 100 mm in size, their facility can easily accommodate an upgrade for the production of gratings with dimensions of 200 by 280 mm. It is their desire to implement such an upgrade in the very near future. This would allow this interesting and valuable technology to be implemented in astronomical instruments on moderately large telescopes.

With the advent of 8 and 10 meter class telescopes, even gratings of 200 mm in size are becoming too small. The demand is increasing for gratings with sizes of 300 to 400 mm. Classical surface gratings are difficult and expensive to produce due to the wear of the diamond as the grating is ruled. Grating mosaics are possible (e.g. the Echelle grating in HIRES on Keck has 3 gratings to form a 300 by 1200 mm mosaic[19]), but complicated and also costly. State-of-the-art holographic exposure and processing technology is at a level where the production of very large VP gratings could be possible (greater than 600 mm). Indeed, holographically generated surface-relief gratings are already achieving rather large dimensions.

5.6 Wavelength regime

KOSI currently fabricates gratings used in the visible and has recently started producing gratings for use at 1.5 µm. There has not yet been any effort to produce a VP diffraction grating further towards the infrared. Future efforts may attempt to exploit the transmittance of dichromated gelatin out to 2.8 µm. Behavior of dichromated gelatin at cryogenic temperatures would also need some study.

5.7 Line density and diffraction angle

Gratings are currently fabricated with line densities between 300 and 6000 l/mm. Gratings with diffraction angles of up to 72 degrees have been produced at KOSI. Such high diffraction angle gratings are typically immersed to minimize reflection losses on the air-to-glass substrate surfaces.

5.8 Immersed gratings

Immersion of a classical surface grating is another approach for achieving high resolution with a relatively small grating[20] but is difficult due to the fragile nature of the ruled surface. VP gratings, by their nature, are easily immersed.

5.9 High order diffraction gratings

Little study has been expended on the performance of VP gratings at diffraction orders other than zeroth or first. What has been published[21,22,23] and the behavior of the NOAO test grating suggest that it may be possible to fabricate a relatively high order diffraction VP grating. An Echelle-like VP grating could possibly provide greater dispersing power over classical Echelles, especially given the simplicity of immersing a VP grating. Limitations for very high order gratings ($m>3$) may, however, arise from the inability of current holographic materials to achieve the required refractive index modulation for efficient diffraction into those high orders. Further theoretical and empirical study is needed.

5.10 Aberration correction gratings

Non-dispersive, VP holograms are currently used in military head-up display combiners that incorporate aberration correction within the hologram itself. Similar aberration correction can likely be incorporated into VP holographic gratings[24] in a similar fashion to current, concave, holographic, surface-relief gratings.

5.11 Tunable spectrographs

The nature of the test VP grating raises the possibility that a single grating can have a range of performance characteristics depending on the configuration of the spectrograph in which it is used. Such versatility from a single grating is not available with surface-relief gratings. With VP grating technology, it is possible to think of a spectrograph in which the peak efficiency and dispersive power can be tuned to the desired wavelength of interest with a simple change in both the grating angle and the angle between the collimator and the camera (see Figure 10). Although some complexity is added to the spectrograph housing, the need for separate gratings is eliminated or minimized. A simple, fiber-fed, bench-mounted spectrograph could easily accommodate these adjustments, making the instrument much more versatile than a spectrograph with a classical surface grating.

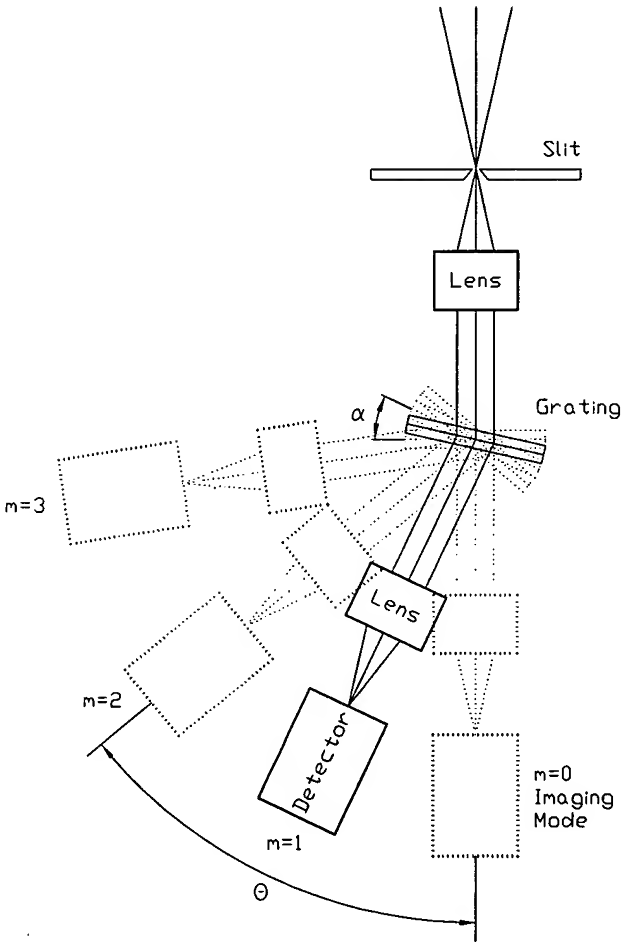

Figure 10. *Schematic of a tunable spectrograph concept in which the camera axis angle (θ) and grating angle (α) are allowed to tilt in order to change the order of diffraction or to peak up the efficiency of the desired wavelength.*

6. CONCLUSIONS

Volume-phase holographic gratings diffract light through a mechanism that is somewhat different from surface-relief grating structures. With VP gratings, one can achieve higher diffraction efficiencies, higher dispersion for transmissive gratings, and a range of versatility that is not possible with surface-relief gratings. Eventual utilization of this technology into astronomical spectrographs will enhance, complement, and possibly replace the suite of spectroscopic facilities currently in use.

7. ACKNOWLEDGEMENTS

S. Barden wishes to thank S. Wolff for the funds to purchase the test grating and to establish a collaboration with Kaiser Optical Systems, Inc. Appreciation also goes to Di Harmer for her assistance in performing the on-sky testing of the grating. We also give thanks to Dan Schroeder and Richard Elston for their input into early and ongoing discussions regarding the utilization of this technology in astronomy.

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retarder cell

See PREVIOUS | NEXT term in listing

Definition:

A device that uses nematic liquid crystals sandwiched between fused silica substrates to change the phase of polarized light. The cell is tunable from half-wave to zero retardation because variation of the applied voltage results in different degrees of birefringence in the liquid crystal.

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Copy of the Corresponding Page of the Patent Rules applicable at the time the application was filed

material to patentability is deemed to be satisfied if all information known to be material to patentability of any claim issued in a patent was cited by the Office or submitted to the Office in the manner prescribed by §§ 1.97(b)-(d) and 1.98. However, no patent will be granted on an application in connection with which fraud on the Office was practiced or attempted or the duty of disclosure was violated through bad faith or intentional misconduct. The Office encourages applicants to carefully examine:

(1) Prior art cited in search reports of a foreign patent office in a counterpart application, and

(2) The closest information over which individuals associated with the filing or prosecution of a patent application believe any pending claim patentably defines, to make sure that any material information contained therein is disclosed to the Office.

(b) Under this section, information is material to patentability when it is not cumulative to information already of record or being made of record in the application, and

(1) It establishes, by itself or in combination with other information, a *prima facie* case of unpatentability of a claim; or

(2) It refutes, or is inconsistent with, a position the applicant takes in:

(i) Opposing an argument of unpatentability relied on by the Office, or

(ii) Asserting an argument of patentability.

A *prima facie* case of unpatentability is established when the information compels a conclusion that a claim is unpatentable under the preponderance of evidence, burden-of-proof standard, giving each term in the claim its broadest reasonable construction consistent with the specification, and before any consideration is given to evidence which may be submitted in an attempt to establish a contrary conclusion of patentability.

(c) Individuals associated with the filing or prosecution of a patent application within the meaning of this section are:

(1) Each inventor named in the application;

(2) Each attorney or agent who prepares or prosecutes the application; and

(3) Every other person who is substantively involved in the preparation or prosecution of the application and who is associated with the inventor, with the assignee or with anyone to whom there is an obligation to assign the application.

(d) Individuals other than the attorney, agent or inventor may comply with this section by disclosing information to the attorney, agent, or inventor.

(e) In any continuation-in-part application, the duty under this section includes the duty to disclose to the Office all information known to the person to be material to patentability, as defined in paragraph (b) of this section, which became available between the filing date of the prior application and the national or PCT international filing date of the continuation-in-part application.

[42 FR 5593, Jan. 28, 1977; paras. (d) & (e) - (i), 47 FR 21751, May 19, 1982, effective July 1, 1982; para. (c), 48 FR 2710, Jan. 20, 1983, effective Feb. 27, 1983; paras. (b) and (j), 49 FR 554, Jan. 4, 1984, effective Apr. 1, 1984; paras. (d) and (h), 50 FR 5171, Feb. 6, 1985, effective Mar. 8, 1985; para. (e), 53 FR 47808, Nov. 28, 1988, effective Jan. 1, 1989; 57 FR 2021, Jan. 17, 1992, effective Mar. 16, 1992; para. (e) added, 65 FR 54604, Sept. 8, 2000, effective Nov. 7, 2000]

§ 1.57 [Reserved]

[48 FR 2710, Jan. 20, 1983, effective Feb. 27, 1983]

§ 1.58 Chemical and mathematical formulae and tables.

(a) The specification, including the claims, may contain chemical and mathematical formulas, but shall not contain drawings or flow diagrams. The description portion of the specification may contain tables; claims may contain tables either if necessary to conform to 35 U.S.C. 112 or if otherwise found to be desirable.

(b) Tables that are submitted in electronic form (§§ 1.96(c) and 1.821(c)) must maintain the spatial relationships (*e.g.*, columns and rows) of the table elements and preserve the information they convey. Chemical and mathematical formulae must be encoded to maintain the proper positioning of their characters when displayed in order to preserve their intended meaning.

(c) Chemical and mathematical formulae and tables must be presented in compliance with § 1.52(a) and (b), except that chemical and mathematical formulae or tables may be placed in a landscape orienta-

Copy of MPEP 608 .01 (p), version 8, first revision, revised February 2003

Form paragraph 6.28.01 may be used where the examiner, for reasons other than faulty English, requires a substitute specification.

¶ 6.28.01 Substitute Specification Required by Examiner

A substitute specification **[1]** the claims is required pursuant to 37 CFR 1.125(a) because **[2]**.

A substitute specification filed under 37 CFR 1.125(a) must only con-tain subject matter from the original specification and any previously entered amendment under 37 CFR 1.121. If the substitute specification contains additional subject matter not of record, the substitute specifica-tion must be filed under 37 CFR 1.125(b) and must be accompanied by: 1) a statement that the substitute specification contains no new matter; and 2) a marked-up copy showing the amendments to be made via the substi-tute specification relative to the specification at the time the substitute specification is filed.

Examiner Note:

1. In bracket 1, insert either -- excluding-- or -- including--.
2. In bracket 2, insert clear and concise examples of why a new specifi-cation is required.
3. A new specification is required if the number or nature of the amendments render it difficult to consider the application or to arrange the papers for printing or copying, 37 CFR 1.125.
4. See also form paragraph 13.01 for partial rewritten specification.
5. 37 CFR 1.125(b) provides applicants with the right of entry of substitute specifications, under the conditions set forth in the section, in applications other than reissue applications (37 CFR 1.125(d)) that have not been required by the examiner.

37 CFR 1.125(b) applies to a substitute specification voluntarily filed by the applicant. A substitute specification, excluding claims, may be voluntarily filed by the applicant at any point up to the payment of the issue fee provided it is accompanied by (1) a statement that the substitute specification includes no new matter, and (2) a marked-up copy of the substitute specification showing the matter being added to and the matter being deleted from the specification of record. Numbering the paragraphs of the specification of record is not considered a change that must be shown under 37 CFR 1.125(b)(2). 37 CFR 1.125(b). The Office will accept a substitute specification voluntarily filed by the applicant if the requirements of 37 CFR 1.125(b) are satisfied.

37 CFR 1.125(c) requires a substitute specification filed under 37 CFR 1.125(a) or (b) be submitted in clean form without markings as to amended material. The paragraphs of any substitute specification, other than the claims, should be individually numbered in Arabic numerals so that any amendment to the specification may be made by replacement paragraph in accordance with 37 CFR 1.121(b)(1).

A substitute specification filed under 37 CFR 1.125(b) must be accompanied by a statement indicating that no new matter was included. There is no obligation on the examiner to make a detailed comparison between the old and the new specifications for determining whether or not new matter has been added. If, however, an examiner becomes aware that new matter is present, objection thereto should be made.

The filing of a substitute specification rather than amending the original application has the advantage for applicants of eliminating the need to prepare an amendment of the specification. If word processing equipment is used by applicants, substitute specifications can be easily prepared. The Office receives the advantage of saving the time needed to enter amendments in the specification and a reduction in the number of printing errors. A substitute specification is not permitted in a reissue application or in a reexamination proceeding. 37 CFR 1.125(d).

A substitute specification which complies with 37 CFR 1.125 should normally be entered. The examiner should write “Enter” or “OK to Enter” and his or her initials in ink in the left margin of the first page of the substitute specification. A substitute specification which is denied entry should be so marked.

Form paragraph 6.28.02 may be used to notify applicant that a substitute specification submitted under 37 CFR 1.125(b) has not been entered.

¶ 6.28.02 Substitute Specification Filed Under 37 CFR 1.125(b) Not Entered.

The substitute specification filed **[1]** has not been entered because it does not conform to 37 CFR 1.125(b) because: **[2]**

Examiner Note:

1. In bracket 2, insert statement of why the substitute specification is improper, for example:

-- the statement as to a lack of new matter under 37 CFR 1.125(b) is missing--,

-- a marked-up copy of the substitute specification has not been supplied (in addition to the clean copy)--;

-- a clean copy of the substitute specification has not been supplied (in addition to the marked-up copy)--; or,

-- the substitute specification has been filed:

- in a reissue application or in a reexamination proceeding, 37 CFR 1.125(d)-, or

- after payment of the issue fee-, or

- containing claims (to be amended)- --.

See MPEP § 714.20 regarding entry of amendments which include an unacceptable substitute specification.

For new matter in amendment, see MPEP § 608.04.

For application prepared for issue, see MPEP § 1302.02.

608.01(r) Derogatory Remarks About Prior Art in Specification

The applicant may refer to the general state of the art and the advance thereover made by his or her invention, but he or she is not permitted to make derogatory remarks concerning the inventions of others. Derogatory remarks are statements disparaging the products or processes of any particular person other than the applicant, or statements as to the merits or validity of applications or patents of another person. Mere comparisons with the prior art are not considered to be disparaging, *per se*.

608.01(s) Restoration of Canceled Matter

Canceled text in the specification can be reinstated only by a subsequent amendment presenting the previously canceled matter as a new insertion. 37 CFR 1.121(b)(4). A claim canceled by amendment (deleted in its entirety) may be reinstated only by a subsequent amendment presenting the claim as a new claim with a new claim number. 37 CFR 1.121(c)(2). See MPEP § 714.24.

608.01(t) Use in Subsequent Application

A reservation for a future application of subject matter disclosed but not claimed in a pending application will not be permitted in the pending application. 37 CFR 1.79; MPEP § 608.01(e).

No part of a specification can normally be transferred to another application. Drawings may be transferred to another application only upon the granting of a petition filed under the provisions of 37 CFR 1.182. See MPEP § 608.02(i).

608.01(u) Use of Formerly Filed Incomplete Application

Parts of an incomplete application which have been retained by the Office may be used as part of a complete application if the missing parts are later supplied. See MPEP § 506 and § 506.01.

608.01(v) Trademarks and Names Used in Trade

The expressions "trademarks" and "names used in trade" as used below have the following meanings:

Trademark: a word, letter, symbol, or device adopted by one manufacturer or merchant and used to identify and distinguish his or her product from those of others. It is a proprietary word, letter, symbol, or device pointing distinctly to the product of one producer.

Names Used in Trade: a nonproprietary name by which an article or product is known and called among traders or workers in the art, although it may not be so known by the public, generally. Names used in trade do not point to the product of one producer, but they identify a single article or product irrespective of producer.

Names used in trade are permissible in patent applications if:

(A) Their meanings are established by an accompanying definition which is sufficiently precise and definite to be made a part of a claim, or

(B) In this country, their meanings are well-known and satisfactorily defined in the literature.

Condition (A) or (B) must be met at the time of filing of the complete application.

TRADEMARKS

The relationship between a trademark and the product it identifies is sometimes indefinite, uncertain, and arbitrary. The formula or characteristics of the product may change from time to time and yet it may continue to be sold under the same trademark. In patent specifications, every element or ingredient of the product should be set forth in positive, exact, intelligible language, so that there will be no uncertainty as to what is meant. Arbitrary trademarks which are liable to mean different things at the pleasure of manufacturers do not constitute such language. *Ex Parte Kattwinkle*, 12 USPQ 11 (Bd. App. 1931).

However, if the product to which the trademark refers is set forth in such language that its identity is clear, the examiners are authorized to permit the use of the trademark if it is distinguished from common descriptive nouns by capitalization. If the trademark has a fixed and definite meaning, it constitutes

sufficient identification unless some physical or chemical characteristic of the article or material is involved in the invention. In that event, as also in those cases where the trademark has no fixed and definite meaning, identification by scientific or other explanatory language is necessary. *In re Gebauer-Fuelnegg,* 121 F.2d 505, 50 USPQ 125 (CCPA 1941).

The matter of sufficiency of disclosure must be decided on an individual case-by-case basis. *In re Metcalfe,* 410 F.2d 1378, 161 USPQ 789 (CCPA 1969).

Where the identification of a trademark is introduced by amendment, it must be restricted to the characteristics of the product known at the time the application was filed to avoid any question of new matter.

If proper identification of the product sold under a trademark, or a product referred to only by a name used in trade, is omitted from the specification and such identification is deemed necessary under the principles set forth above, the examiner should hold the disclosure insufficient and reject on the ground of insufficient disclosure any claims based on the identification of the product merely by trademark or by the name used in trade. If the product cannot be otherwise defined, an amendment defining the process of its manufacture may be permitted. Such amendments must be supported by satisfactory showings establishing that the specific nature or process of manufacture of the product as set forth in the amendment was known at the time of filing of the application.

Although the use of trademarks having definite meanings is permissible in patent applications, the proprietary nature of the marks should be respected. Trademarks should be identified by capitalizing each letter of the mark (in the case of word or letter marks) or otherwise indicating the description of the mark (in the case of marks in the form of a symbol or device or other nontextual form). Every effort should be made to prevent their use in any manner which might adversely affect their validity as trademarks.

Form paragraph 6.20 may be used.

¶ 6.20 Trademarks and Their Use

The use of the trademark **[1]** has been noted in this application. It should be capitalized wherever it appears and be accompanied by the generic terminology.

Although the use of trademarks is permissible in patent applications, the proprietary nature of the marks should be respected and every effort made to prevent their use in any manner which might adversely affect their validity as trademarks.

Examiner Note:

Capitalize each letter of the word in the bracket or include a proper trademark symbol, such as ™ or ® following the word.

The examiner should not permit the use of language such as "the product X (a descriptive name) commonly known as Y (trademark)" since such language does not bring out the fact that the latter is a trademark. Language such as "the product X (a descriptive name) sold under the trademark Y" is permissible.

The use of a trademark in the title of an application should be avoided as well as the use of a trademark coupled with the word "type", e.g., "Band-Aid type bandage."

In the event that the proprietary trademark is a "symbol or device" depicted in a drawing, either the brief description of the drawing or the detailed description of the drawing should specify that the "symbol or device" is a registered trademark of Company X.

The owner of a trademark may be identified in the specification.

Technology Center Directors should reply to all trademark misuse complaint letters and forward a copy to the editor of this manual.

See Appendix I for a partial listing of trademarks and the particular goods to which they apply.

INCLUSION OF COPYRIGHT OR MASK WORK NOTICE IN PATENTS

37 CFR 1.71. Detailed description and specification of the invention

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(d) A copyright or mask work notice may be placed in a design or utility patent application adjacent to copyright and mask work material contained therein. The notice may appear at any appropriate portion of the patent application disclosure. For notices in drawings, see § 1.84(s). The content of the notice must be limited to only those elements provided for by law. For example, "©1983 John Doe" (17 U.S.C. 401) and "*M* John Doe" (17 U.S.C. 909) would be properly limited and, under current statutes, legally sufficient notices of copyright and mask work, respectively. Inclusion of a copyright or mask work notice will be permitted only if the authorization language set forth in paragraph (e) of this section is included at the beginning (preferably as the first paragraph) of the specification.

(e) The authorization shall read as follows:

RELATED PROCEEDINGS APPENDIX

No related proceedings.